JOURNAL of the STACKS

AIR POLLUTION CONTROL ASSOCIATION

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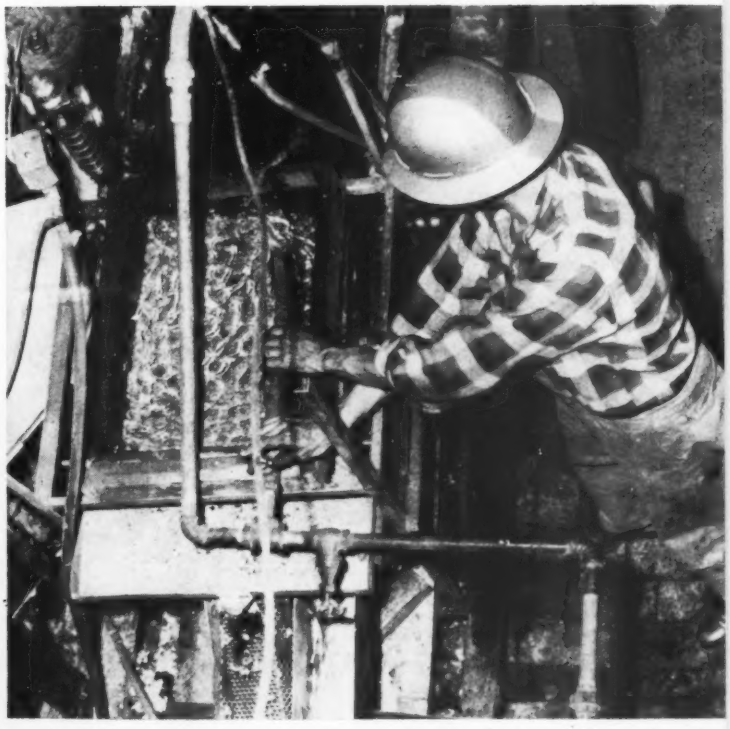

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(See Page 53)

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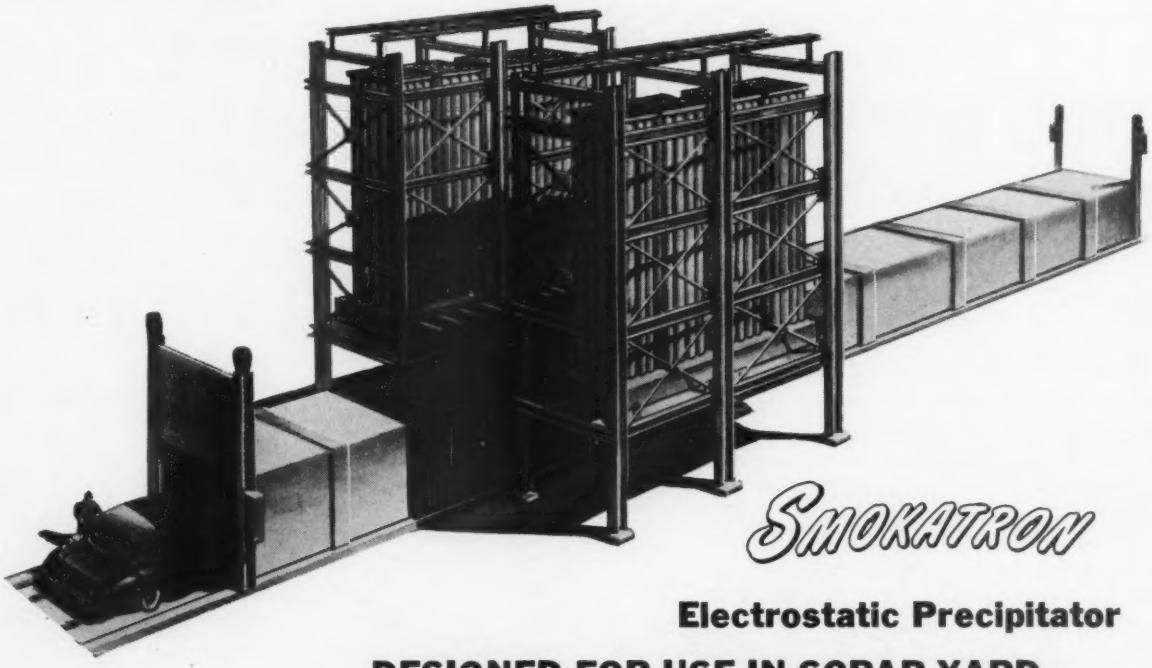

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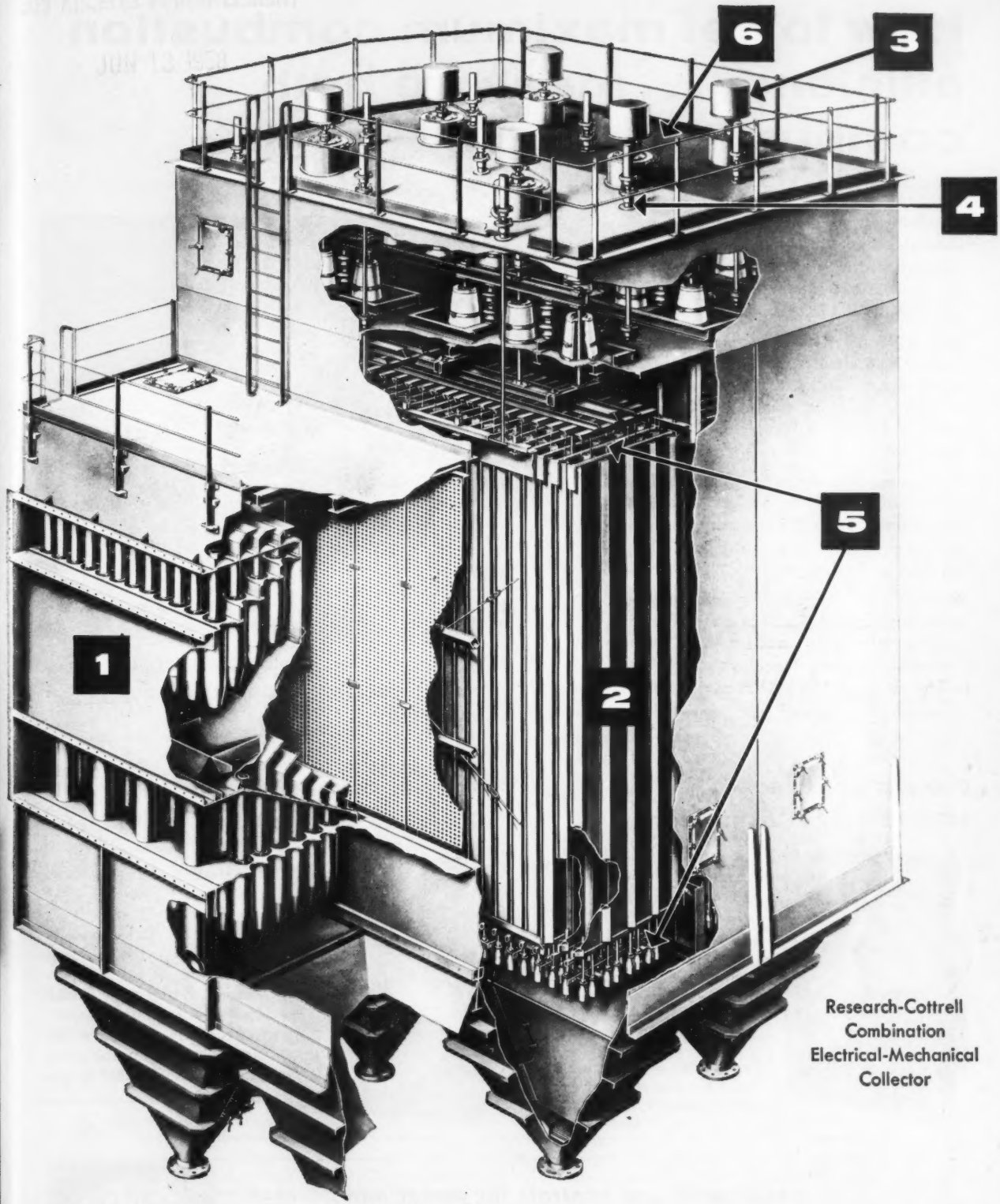

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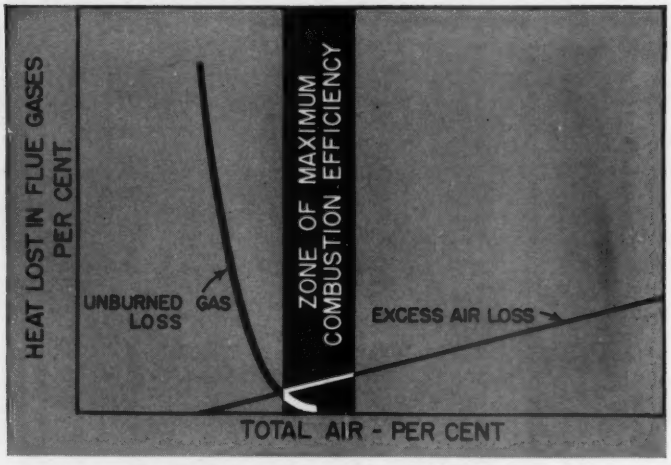
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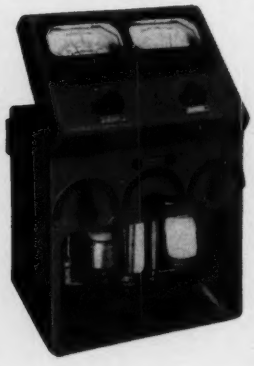

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JOURNAL OF THE AIR POLLUTION CONTROL ASSOCIATION

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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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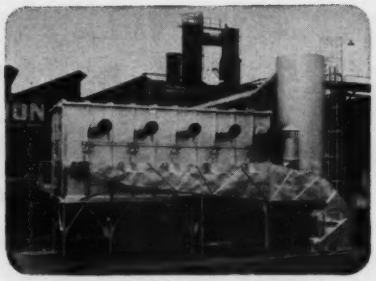

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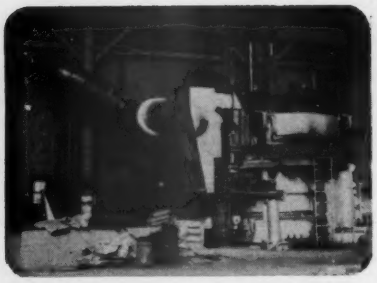

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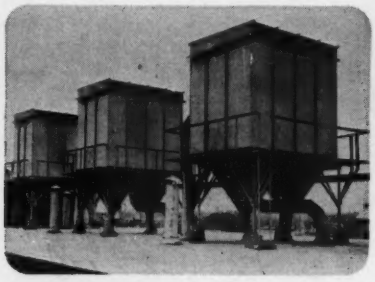

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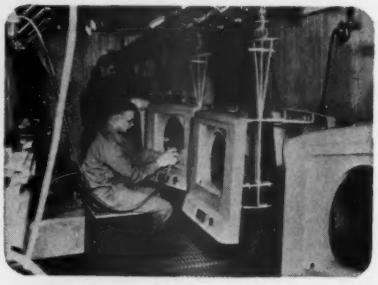

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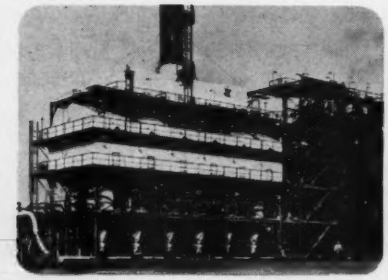

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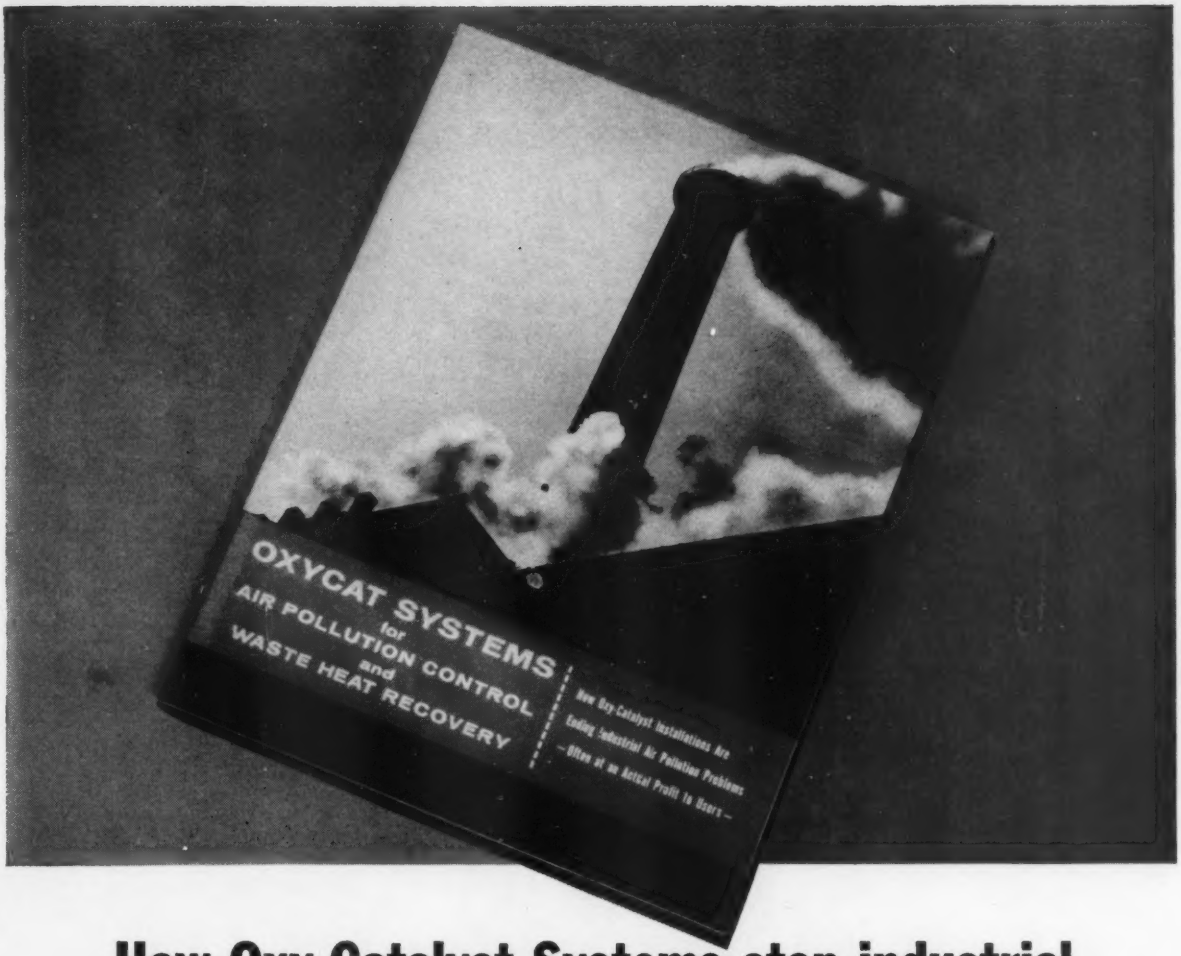

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Damage to Vegetation from Polluted Atmospheres*

JOHN T. MIDDLETON, ELLIS F. DARLEY, AND ROBERT F. BREWER

University of California

Riverside, Calif.

Damage to vegetation from polluted atmospheres has been recognized for more than a century. Early interest in air pollution centered largely on smoke and fumes from industrial wastes, particularly those of chemical manufacture, smelting, ceramic production, and coal and petroleum combustion effluents. Vegetation damage has increased with industrialization and urban development. Whereas the principal plant toxicants recognized several decades ago were sulfur dioxide and fluorine, in the last decade a new group of airborne phytotoxicants has been described and identified as oxidants. The principal source of these oxidants is believed to be photolysis reaction products of auto exhaust. Atmospheric contaminants responsible for damage to vegetation may be described as particulates — such as dusts and acid aerosols — and gases — such as sulfur dioxide, halogens, oxidized organics, ozone, nitrogen dioxide, hydrogen sulfide, ammonia, and carbon monoxide. Of these diverse pollutants, gases generally cause more damage to plants than do particulates.

Particulates

A number of materials occur in the atmosphere as particulates — such as carbon and cement dusts — which form undesirable deposits on agricultural produce. Injury to leaves and fruits of many plants may result from acid aerosols, originating from the combustion of sulfur-containing fuels, smelting of ores, and chemical manufacture. Sulfuric acid aerosols[10] produce small to large spots on the upper exposed surface of leaves (Fig. 1). Although injury usually occurs during periods of fog when the droplets become large enough to settle out and the leaf readily wets, acid aerosol damage also occurs near combustion effluents in the absence of fog when the gas effluent dew point permits droplet formation. Thomas[13] reports that acid aerosols may persist for weeks under certain conditions as spheres on the surface of dry leaves without producing injury. However, when the same leaves are wet with a fine mist of water, the spotting typical of acid aerosol injury is produced.

Sulfur Dioxide

Sulfur dioxide is one of the oldest known air pollutants recognized as causing significant damage to vegetation. Indeed, in several instances, damage to vegetation was the first indication that the air in the vicinity of certain industries was being polluted. The effects of this gas on plants have been studied for more than 75 years.

Litigation over crop losses resulted in extensive investigation at the Selby smelter in California about 1905 and at the Trail smelter in British Columbia in the early 1930's. In the latter case it was estimated that losses to forest and agricultural vegetation amounted to $350,000 in the period 1926 to 1931 and to about $78,000 from 1932 to 1937.[12] These losses are low compared to those attributed to oxidant and fluorine, to be described below. The development and use of control devices by research and industry has reduced sulfur dioxide loss to very low values.

Injury to plant leaves exposed to sulfur dioxide has been described as either acute or chlorotic.[13] Acute injury occurs following the rapid absorption of sufficient gas to kill the leaf tissues. Tissues in the interveinal and marginal areas of affected leaves collapse and assume a water-soaked appearance; later they become desiccated and bleached (Fig. 2). It is characteristic of the injury that the veins remain green. Chlorotic injury — a gradual yellowing of affected leaves, later becoming white — is caused by rapid absorption of less amounts of the gas than would cause acute symptoms or by exposure over a long period of time to sublethal concentrations.

It is important to note that leaf destruction is more directly dependent upon the amount of gas actually

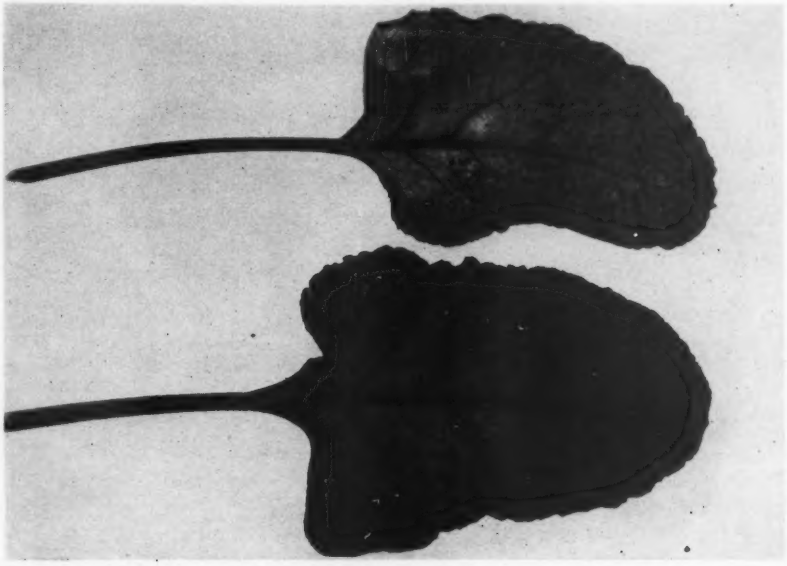

Fig. 1. Table beet leaves, showing acid aerosol injury on upper surface of leaf on top and their extension to the lower surface of leaf on bottom. The small punctate spots characterize this type of injury and are uniformly dispersed over the leaf area. The upper left-hand area of leaf on top was protected by a covering leaf.

*Presented at the 22nd Midyear Meeting of the American Petroleum Institute's Division of Refining, in the Sheraton Hotel, Philadelphia, Pa., May 14, 1957.

absorbed than on the concentration of the gas in the air. Exposures which would result in severe injury to given plants under one set of conditions could be innocuous under another.

Plant species vary in their reactions to sulfur dioxide. Alfalfa and barley are among the most sensitive. Incipient damage markings on alfalfa, exposed under conditions of maximum sensitivity, occur after 1 hr. at 1.25 ppm.,[14] and leaves are severely damaged at 5 ppm. P. G. O'Gara studied the relative susceptibility of over 300 plant species, and Thomas and Hill[16] list several of these. Compared to the exposure required to damage alfalfa, oats require 1.3 times the exposure, corn 4 times, and muskmelon almost 8 times.

The development of control devices has reached the point where it is possible to reduce the concentration of sulfur dioxide to nontoxic levels of 0.1 to 0.3 ppm. Damage to vegetation can be expected now only where there is inadvertent spilling of the chemical.

Plant damage from smog in the Los Angeles basin has been reported lessened by the presence of nontoxic concentrations of sulfur dioxide in the polluted air. Thomas *et al.*[15] cited the experience of one company wherein plants were placed in special chambers, some of which received polluted air while others received the same air after it had been washed in water scrubbers. Plants receiving the scrubbed air from which the sulfur dioxide had been removed were more severely damaged than those receiving the air containing sulfur dioxide. This indicated some interfering action on the part of sulfur dioxide.

Further evidence of this interference with damage is reported by Haagen-Smit *et al.*[4] When 0.1 ppm. sulfur dioxide was mixed with plant-damaging concentrations of the reaction products of ozone and gasoline, no plant damage occurred. It was concluded that sulfur dioxide reduced the plant-damaging oxidant.

At Riverside this interference phenomenon was tested further. Pinto beans were exposed to sulfur dioxide and ozone separately and to mixtures of the two gases. Comparable amounts of damage to pinto beans were produced when they were exposed for 2 hrs. to 1.5 ppm. of sulfur dioxide or to 0.25 ppm. of ozone. The ozone symptoms were characteristic and consisted of bleaching confined to the upper surface of the leaves.

When the two pure gases were mixed in an 18-li. glass bottle, they coexisted for 3 weeks without reacting. Levels of ozone at 0.3 ppm. mixed with 1.5 ppm. sulfur dioxide in a dynamic flow system were unchanged after a 6-min. residence period. The extent of injury to plants exposed to these mixtures indicates that there is no interference by sulfur dioxide with the amount of damage caused by ozone. However, ozone did interfere to some extent with the development of expected sulfur dioxide injury. If

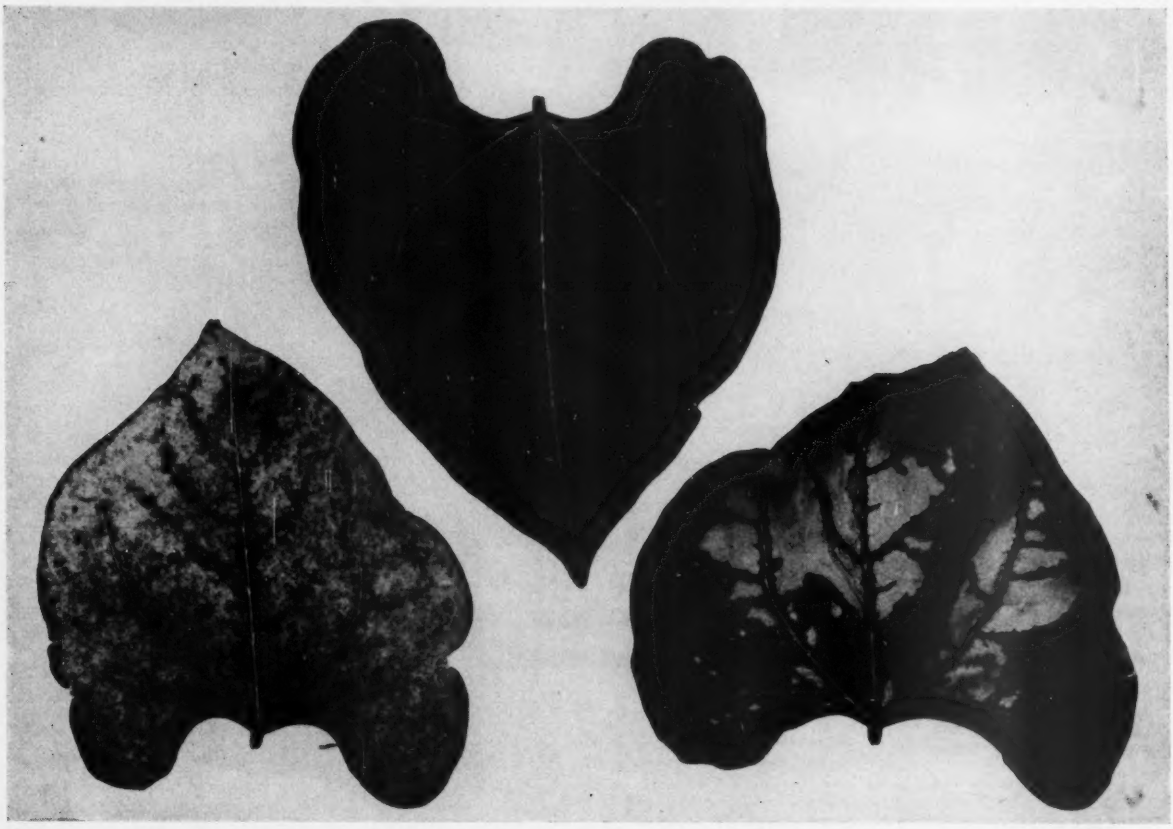

Fig. 2. Upper surface of primary leaves of pinto bean exposed to ozone (left), nonfumigated (center), and sulfur dioxide (right). Minute speckling and chlorosis restricted to upper surface is characteristic of ozone injury. Bleaching and destruction of leaf tissue through the leaf is characteristic of acute sulfur dioxide injury.

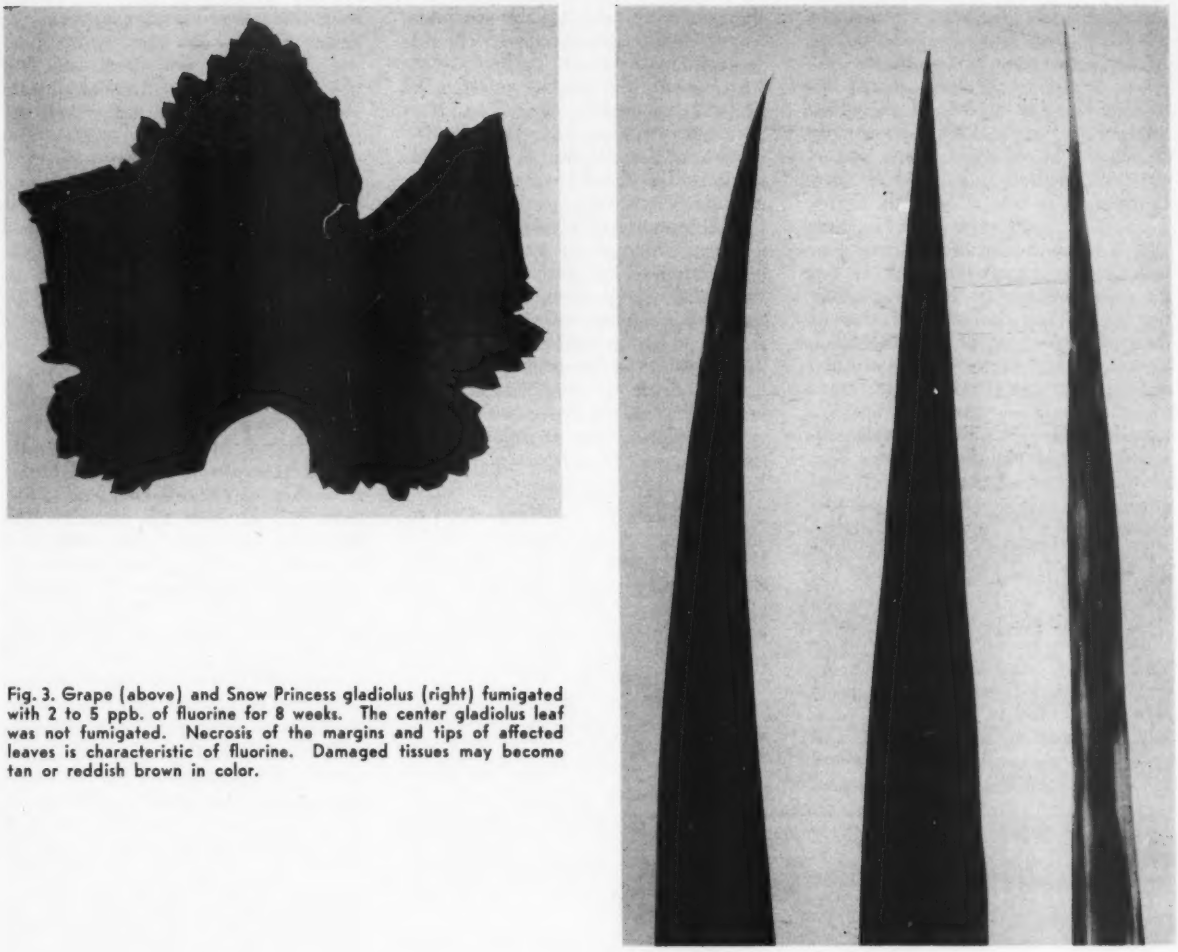

Fig. 3. Grape (above) and Snow Princess gladiolus (right) fumigated with 2 to 5 ppb. of fluorine for 8 weeks. The center gladiolus leaf was not fumigated. Necrosis of the margins and tips of affected leaves is characteristic of fluorine. Damaged tissues may become tan or reddish brown in color.

the sulfur dioxide-ozone ratio was at or less than 4:1, ozone appeared to interfere with the development of injury expected from sulfur dioxide. If the ratio was increased to 6:1, or higher, the symptoms of both gases appeared on the same leaves and there was no evidence of any interference. This is an example of the usefulness of plants in detecting mixtures of air pollutants.

Fluorine

Fluorine injury to vegetation and livestock is considered the most important nation-wide air pollution problem in the United States. The problem is not new. Fluoride injury was recognized and described over 50 years ago in Germany. There, as is usually the case with fluorine pollution, damage to livestock and vegetation was observed in the vicinity of certain chemical, metals, and ceramic industries. In this country the importance of the fluorine pollution problem has increased with the rapid expansion of chemical and metals industries. Serious damage to vegetation and/or livestock, resulting from fluorine emitted by neighboring industries, has been observed in Florida, Idaho, Montana, New Jersey, Oregon, Tennessee, and Washington. In 1950 extensive fluorine damage to ponderosa pine in Spokane County, Washington, produced a *blight area* 3.5 miles wide and 12 miles long[1] At present, claims for damage and litigations arising out of alleged fluorine damage in the states of Utah, Florida, and Idaho total nearly three millions of dollars.

Fluorine and its compounds are released when ores, clays, or fluxes containing this element are heated to extremely high temperatures. Industries known to emit fluorides in the flue gases include steel mills, aluminum reduction plants, ceramic works, uranium purification installations, and superphosphate factories. Although elemental fluorine might be evolved as such in some of the above processes, the element is so reactive that the likelihood of its remaining in the elemental state is extremely remote. Gaseous silicon tetrafluoride, hydrofluoric acid, and fluorosilicic acid are some of the forms of fluorine which are probably released in flue gases. Cryolite, Na_3AlF_6, a soluble and somewhat volatile material used as a source of aluminum in the aluminum reduction industry and occasionally in agriculture as an insecticide, is also a potential source of fluorine in the atmosphere and in vegetation.

Many species of plants are severely injured when exposed for prolonged periods to concentrations of as little as 0.5 to 5 ppb. F as HF (ppb. fluorine as hydrofluoric acid) in the atmos-

phere. Similar injury can also be produced by shorter exposures to higher concentrations. Plants exposed to toxic concentrations of hydrogen fluoride or one of the other phytotoxic forms of fluorine usually develop gray or light green water-soaked marginal lesions which may in time turn tan or reddish brown (Fig. 3). Such injury may appear within a few hours after exposure or may not appear for a week or ten days following exposure, depending on the species, the concentration of fluorine phytotoxicant, and the duration of the exposure. With continued exposure the marginal necrotic areas of netted leaves — grape and apricot, for instance — spread inward toward the midvein until a large part of the leaf is affected or until leaf abscission takes place. With parallel veined leaves — grasses, gladiolus, *etc.* — injury usually first appears at the tip and slowly spreads down the leaf. Under certain circumstances, symptoms resembling those just mentioned above may be caused by other agents. For instance, toxic concentrations of chlorine in the soil, moisture deficit due to insufficient rainfall or irrigation, drying winds, and excess salt accumulations in the soil are some of the factors known to produce similar injury patterns on grapes. Chemical analysis of the injured foliage will indicate an abnormally high fluorine content if fluorine injury is a factor to be considered. Plants exposed to fluorine in the atmosphere continue to accumulate fluoride so long as they are alive and growing. Thus, analysis of vegetation from areas where fluorine pollution is suspected will not only indicate the relative extent and intensity of the pollution but can also be used to pinpoint the source or sources of the fluorine. Fluorine content of foliage will increase as one approaches the source from a given direction. This technique has been used in southern California for pinpointing major sources of fluorine pollution.[6]

The various species and varieties of plants differ widely in their susceptibility to fluorine injury. Gladiolus, apricot, pine, and sweet potato have been reported as being particularly sensitive to hydrogen fluoride gas.[13] To this list should be added the grape. Results of simultaneous fumigations of 12 varieties of wine grape vines and two varieties of gladiolus — including variety Snow Princess — with 2 to 5 ppb. F as HF indicated that several of the grape varieties were nearly as susceptible to fluorine injury as were the gladiolus. These studies also revealed wide differences in sensitivity to fluoride injury among the twelve varieties of grape vines tested. Blue Elba, Burger, and Mission were among the most sensitive, while varieties Zinfandel and Concord were among those most resistant to fluorine injury. Similar differences in sensitivity among different varieties of gladiolus have been reported by Johnson *et al.*[5] With gladiolus it seems that the least sensitive varieties absorb the most fluorine. In the case of wine grapes this relationship between gas absorption and degree of sensitivity does not hold. Several of the most tolerant grape varieties also accumulated the least fluorine.

There are striking differences among species in their capacities to absorb and tolerate fluorine. Grape leaves contained 600 to 1,000 ppm. fluorine, citrus leaves 250 ppm., and gladiolus leaves 300 ppm. fluorine on a dry weight basis after 8 weeks' exposure to 2 to 5 ppb. fluorine. Of the 3 species, gladiolus was the most severely injured. Some varieties of grapes were seriously damaged, others showed little or no evidence of injury. Sweet orange seedlings were apparently not adversely affected by the treatment. There were no leaf symptoms nor decrease in linear growth compared with similar citrus seedlings which received no fluorine.

Of potentially more importance than direct injury to plants is the possible detrimental effect of the plants which have absorbed fluorine on animals which eat the plants. Plants which appear quite normal may contain sufficient fluorine to cause severe injury to livestock. Alfalfa, for instance, will tolerate several hundred ppm. fluorine without producing injury symptoms but animals fed forage containing in excess of 50 ppm. fluorine may develop fluorosis. This disease, characterized by mottled and brittle teeth and abnormally high fluorine concentrations in bones, is common among livestock raised on rangeland adjoining fluoride-emitting industries. It is also common where water supplies are abnormally high in fluorine content due to underground contamination by soluble fluoride deposits.

Oxidants

Damage to leafy vegetable and field crops of a type quite different than that resulting from exposure to sulfur dioxide, halogens, and a number of other air pollutants, was first observed in the Los Angeles area in 1944.[10] The symptoms of this apparently unique injury consist of a silvering, glazing, bronzing, and sometimes necrosis of the lower leaf surface (Fig. 4). Injury to the upper leaf surface typically occurs only after damage to the lower surface is extensive. This type of injury is commonly called smog damage, despite the fact that it is not related to either smoke or fog.

By 1949, injury to crops in Los Angeles County amounted to an estimated loss of $479,495. During 1950, crop damage occurred not only in Los Angeles County, but in Orange, Riverside, and San Bernardino Counties, as well as in the southern San Francisco Bay area. In 1956, economic damage to agriculture was observed in 7 southern and 12 northern California counties. Estimated annual loss to crops now exceeds $5,000,000 in the Los Angeles area and over $1,100,000 in the San Francisco area. It is significant that this serious damage to vegetation in California occurs in areas of greatest population density, lending support to the thesis that urban atmospheric pollution results from man's total activities and not from a limited number of specific industrial sources.[11] Automobile exhaust is believed to be a major contributor to the substances in the atmosphere that produce oxidant. Another large contributor is the burning of trash. Critical observation of vegetation in other metropolitan areas of this country undoubtedly will reveal smog-type damage.

In addition to unique markings on agricultural crops and weeds, the atmospheric pollutants in populated areas and in their contiguous air drainage regions cause marked reduction in growth and production of a variety of economic plants such as tomato, sugar beet, and avocado, without producing leaf symptoms. For lack of adequate techniques the monetary loss attributable to growth suppression and yield reduction has not been estimated.

Since silvering and glazing symptoms appear after periods of aggravated pollution, or smog, it was believed that the atmospheric contaminants responsible for it could perhaps be identified if the same injury could be reproduced experimentally under controlled conditions. Haagen-Smit *et al.*[4] discovered that typical

smog damage could be produced on sensitive indicator plants by exposing them to a mixture of ozone and certain olefin vapors when reacted at high concentration and diluted in an air stream. Leaf symptoms indistinguishable from those found in the field were produced by ozone and butadiene, 1-pentene, 1-hexene, cyclohexene, 3-heptene, 1-octene, 4-nonene, and benzene. They showed that the end product organic acids and aldehydes were not able to produce the unique silvering and bronzing, and therefore suggested that the toxicant must be an ozonide or related peroxide material that was an oxidant.

Mader *et al.*[7] found that formic acid was present in the Los Angeles atmosphere in amounts up to 0.4 ppm. and was the most concentrated of several organic acids studied. They also found that leaves exposed to naturally occurring pollutants or leaves fumigated with mixtures of ozone and hydrocarbons contained up to 170% of the formic acid found in the untreated plants; the amounts of acetic and lactic acids were considerably less than this. They do not give any evidence to indicate that formic acid was responsible for leaf glazing.

The authors have fumigated pinto beans with 8 ppm. of formic acid in a dynamic flow system without damage.

The response of a variety of plants to ozonated hexene has shown that the lower surface of the primary leaves of pinto bean are highly susceptible to damage and that the amount of injury may be visually determined.[8] The upper surface of the pinto bean leaves becomes bleached and chlorotic when exposed to ozone only (Fig. 2). There is no damage to either leaf surface from exposure to gasoline, 1-pentene, or 1-hexene. The amount of injury from either ozone or the reaction products of ozone and certain olefins depends upon the length of fumigation and the concentration of toxicant. When both ozonated olefin and surplus ozone are present, pinto bean leaves exhibit bleaching of the upper leaf surface and bronzing of the lower. The response of the leaf in this case discriminates between the two different oxidants; this is not possible with oxidant measurements made with neutral buffered potassium iodide.

Ozone produces markings on pinto bean leaves at 0.5 ppm. after 10 min. while about 2/3 of the leaf is severely collapsed after 1 hr. The results of a large number of experiments show a positive linear regression of injury to ozone concentration measured by potassium iodide which is statistically significant.

Ozonated hexene, when reacted at a ratio of about 1000 ppm. ozone to 8000 ppm. 1-hexene in a glass reaction vessel which introduces the two gases separately, produces the phytotoxicant only under certain reaction times. In general, the shorter the reaction time the greater is the ozone damage without oxidized hydrocarbon injury, whereas the longer reaction times produce typical smog-type damage without ozone injury. If the reaction is further prolonged, no damage of any sort appears. The results of a number of ozonated hexene experiments show a positive curvilinear regression of injury to oxidant concentration measured by potassium iodide, which is statistically significant. In this case, however, the amount of increase in injury falls off rapidly as the oxidant concentration increases. Further, plant damage typically occurs under controlled fumigations without free ozone as shown by the fact that there is no cracking of rubber strips under tension. It is evident from these experiments that ozonated olefins produce damage to vegetation typical of that observed in naturally polluted atmospheres, and that the phytotoxicant is generated only under certain conditions of reaction time. It is obvious from this that the chemical identity of the toxicant cannot be ascertained from chemical analysis only, but that plants must be employed to report the presence of the biologically active material. Current work is being carried out with the excellent cooperation of the personnel from the Franklin Institute. This research area is being rapidly expand by this joint project, and other suspected phytotoxicants are being studied. The results of these investigations will be reported later.

A number of materials have been tested for their plant-damaging properties, utilizing the Franklin Institute mobile laboratory in South Pasadena. Although typical damage results from exposure to a mixture of 1 ppm. ozone and 10 ppm. 1-pentene (Fig. 5), neither 1-pentene ozonide nor 2-pentene ozonide produces injury on sensitive bean leaves.

A plant damage survey was con-

Fig. 4. Leaves of Romaine lettuce damaged by naturally polluted air in the Los Angeles basin. Silvering, bronzing, or otherwise glazed appearance is typical of damage caused by smog and by ozonated olefins.

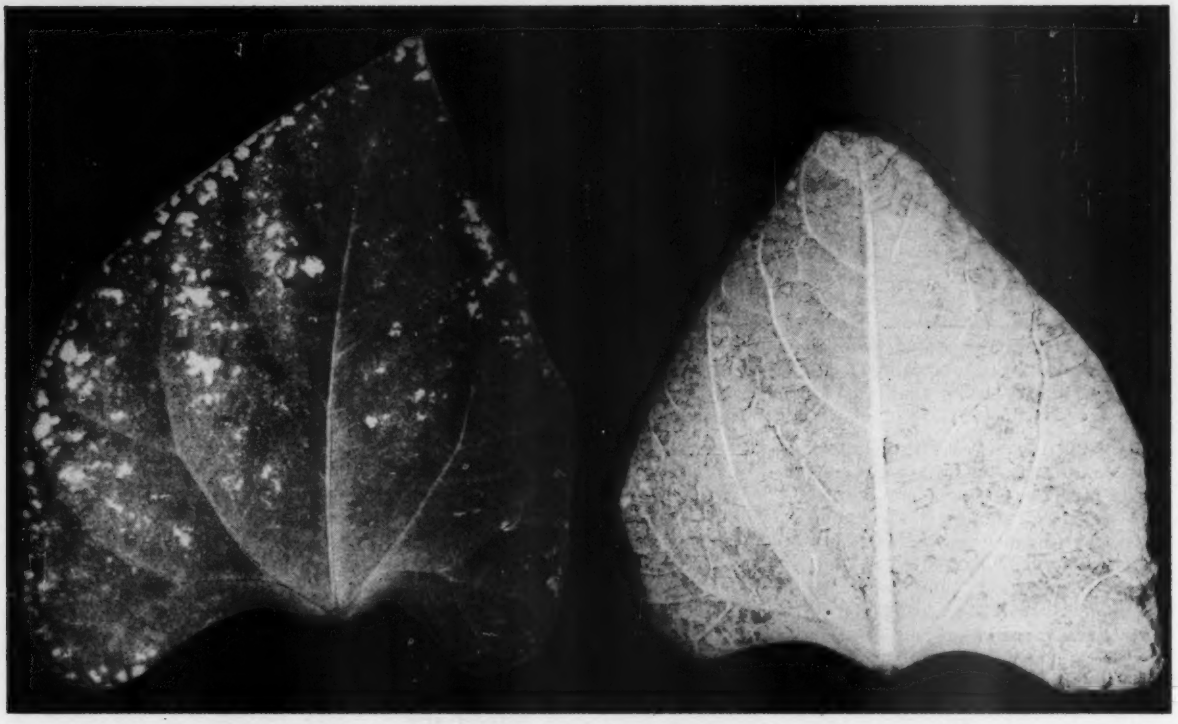

Fig. 5. Pinto bean leaves from a single plant fumigated with mixture of 1 ppm. ozone and 10 ppm. 1-pentene: left, upper surface showing white speckling and larger bleached area typical of ozone damage; right, lower surface showing glazing typical of ozonated olefins.

ducted during two summers, through the cooperation of the Air Pollution Foundation, for the purpose of determining what association existed between various physical and chemical measurements of the atmosphere and the occurrence of plant damage. Pinto beans were used in each survey as the test material. Although typical damage to the lower leaf surface regularly occured during periods of aggravated air pollution when visibility was reduced and oxidant was elevated, there was no evidence of ozone damage to the test plants.

Pinto bean plants were exposed during 1956 in specifically designed exposure boxes which allowed for controlled lighting, air flow rates, and minimum temperature. Plants were placed in boxes which received native air, filtered native air plus ozone generated from oxygen in a glass electrical discharge cell, and native air which also received ozone. Leaves of plants in the activated carbon-filtered air were free from injury when those in unfiltered native air were damaged. Leaves of beans in filtered native air to which ozone was added to produce an oxidant of about 0.25 ppm. developed typical ozone damage. Ozone damage symptoms appeared on leaves of bean in the boxes receiving native unfiltered air to which ozone had been added on days with low natural oxidant, but on days with elevated natural oxidant, the smog damage was increased and ozone injury did not occur.

These observations may account for the absence of naturally occurring ozone damage in that, although the plants are susceptible to ozone injury, the ozone is sufficiently low on days of low oxidant to be nontoxic, and on days of elevated oxidant the ozone preferentially reacts with compounds in native air to produce smog-type plant toxicants to the exclusion of ozone injury.

Although the oxides of nitrogen are a part of urban air pollution, they are not generally considered to be injurious to vegetation. They usually occur in relatively low concentrations, not exceeding 0.2 to 0.3 ppm. expressed as nitrogen dioxide. Benedict and Breen[2] report that the most sensitive species they studied were injured by 20 ppm. and that the least sensitive ones were damaged by 50 ppm. Symptoms consist of irregular, white to brown, collapsed tissue near the margins.

The authors have found that the pinto bean is much more sensitive to nitrogen dioxide than are the weeds reported on by Benedict and Breen. The threshold concentration for damage was about 3 ppm. for 4- to 8-hr. fumigation. Leaves were completely damaged after a 2-hr. exposure to 30 ppm. In these experiments the injury symptoms were indistinguishable from those produced by sulfur dioxide, though 3 to 4 times the concentration of nitrogen dioxide was required to produce comparable damage.

Ethylene

Ethylene occurs as a gaseous contaminant in air from chemicals manufacture, vehicular traffic, and other combustion effluents such as incinerator gases.

Leaves of some plants, such as marigold, do not develop normally in the presence of 5 pphm. of ethylene in the air, whereas 10 pphm. cause leaf abnormality in tomato. Leaf irregularities and poor flower formation occur in narcissus and tulip at concentrations above 400 pphm. Failure of carnation flowers to open properly and flower drop in snapdragon have been attributed to the tixicity of ethylene. The foliage of orchids is not appreciably affected by ethylene, but the sepals of many Cattleya and

Phalaenopsis flowers wither and dry when exposed to 5 ppb. (parts per billion) (Fig. 6).

Although ethylene affects the flowers of several plants, the gas did not produce damage on pinto bean leaves which were fumigated with 42 ppm. for 38 min.

Miscellaneous

Other gases which cause damage to vegetation, listed in decreasing order of their toxicity, are chlorine, ammonia, hydrogen sulfide, and carbon monoxide.[17] Chlorine is somewhat more toxic than sulfur dioxide, about 1/3 to 1/2 the amount being required to cause damage, but the symptoms of injury from the two gases are quite similar. Injury from ammonia differs from that of other gases in that the whole leaf is affected rather than any particular area. Hydrogen sulfide injury differs in that the youngest leaves of affected plants are damaged rather than the older leaves. Zimmerman reports that plants are sensitive to about 500 ppm. of carbon monoxide and that, at that concentration, animals would be killed by it in a short time.

Although the gases mentioned above are injurious to plants, they are usually not considered significant because their emission arises from accidental losses and concentrations are not sufficiently high to cause damage.

Mercury vapors arising from two sources have caused serious damage to greenhouse roses. In one instance the vapors came from bichloride of mercury which had been applied as a soil drench;[17] in the second the vapors came from paint containing phenyl mercuric compounds.[3] In this case, concentrations of 0.008 ppm. were detected and the injured rose leaves had absorbed up to 3.3 ppm. of mercury on a fresh weight basis.

The recent and spectacular development of organic herbicides has created an air pollution problem through the drift of the chemicals during field application. Very small amounts of the volatile esters of 2,4-D and related materials are carried in wind currents some distance from the site of application and have caused serious damage to crop plants on which they were not intended to be applied.[9] It is estimated that 1 g. of 2,4-D could produce deformation on all of the plants in a 25-acre field of cotton.

From the foregoing discussion it is apparent that vegetation is damaged by polluted atmospheres and that economic losses annually amount to millions of dollars throughout the nation. Plants are useful for the identification and distribution of specific atmospheric contaminants. They can also be used in estimating the levels of pollution as well as providing a passive collection system for subsequent chemical analysis.

We acknowledge with sincere thanks the support of the Smoke and Fumes Committee of the American Petroleum Institute and the Project Advisory Committee. We believe that the project will contribute much knowledge in the field of plant damage by polluted atmospheres.

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Fig. 6. Dry sepal damage of Cattleya orchid due to atmospheric pollution by ethylene. Drying of the tissues between the veins is characteristic and occurs when flowers are exposed to 5 ppb. of thylene.

Courtesy: A.M.A. Arch. Ind. H.—Middleton and Paulus (Dec. 1956)

An Experimental Study of Ragweed Pollen Penetration*†

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The problem of the penetration of small particles, such as ragweed pollen, into structures is one phase of the highly complex general problem of the natural ventilation of structures. This complexity arises because the rate of natural ventilation varies not only with the size, design, and structural details of a building but also with meteorological conditions.

Earlier studies have been primarily concerned with the rate of ventilation as obtained by using a gas such as carbon dioxide as a tracer substance. A measured mass of the gas is released in the room or building under study, mixed thoroughly as by an electric fan, and the rate of decrease of concentration with time measured. A critical review of research in this area up to 1935 has been presented by Masterman, Dunning, and Densham (1935). A large bibliography on the subject to 1940 has been given by Radiation Ltd. (1942), methods of measuring ventilation have been described by Lidwell and Lovelock (1946), and a comprehensive analysis of natural ventilation has been prepared by Bedford (1948). Another bibliography is to be found at the end of Chapter 11 on *Infiltration and Ventilation* in the ASHVE Heating Ventilating Air Conditioning Guide 1954. Recent research using the gas tracer technique has been published by Carne (1946); calculations of the penetration of pollution into an ordinary room have been made by Courvoisier (1950); and Georgii (1954) used simultaneous interior measurements of both gas (CO_2) and an aerosol ($CaCl_2$) in an attempt to separate the 2 components of air exchange: ventilation through the walls and ventilation through cracks, clefts, and chinks.

The present paper gives the methods used and the general results obtained from experimental studies of the penetration of ragweed pollen into test structures as part of the process of natural ventilation. The question of penetration of particulates into buildings is of primary importance in the evaluation of air pollution problems. For example, it has an important bearing in determining appropriate actions to be taken under severe smog conditions. The effectiveness of buildings as *pollen refuges* is of concern to the millions of persons who suffer from hay fever and asthma. The health problems involved have been described by Hewson (1955) and some of the meteorological implications have been discussed by Dingle (1953, 1955, 1957). The size uniformity of pollen such as those of ragweed makes these particles most useful for experimental purposes: the ragweed pollen in these experiments have diam. in the range 18 to 20μ. Relatively little has been published on the behavior of particles in this size range.

Preliminary Experimentation and Results

The site of the first experiments conducted was the roof of the East Engineering Building of the University of Michigan at Ann Arbor. The test structure consisted of 2 small adjacent rooms located on the roof: one room was used for the actual penetration studies; the adjacent room housed the instrumentation required. The experimental procedure, stated briefly, was as follows. Ragweed was first removed from the air of the test room by operating a high-volume bag filter. Then 150 *l.* of air were drawn simultaneously through millipore filters during each of a series of 15-min. intervals: one group of millipore filter units was located in the test room; another filter was located just outside the window of the test room. An oscillating electric fan stirred the air in the room during certain of the tests. Two meteorological instruments were also located outside the test room near the window: a bridled-cup gust accelerometer of the type developed by Hewson and Gill (1944) measured atmospheric turbulence, and the Beckman-Whitley anemometer described by West (1952) measured the wind speed. The pollen caught on each filter was counted under the microscope using 100X magnification.

The above procedures were designed to determine rates of penetration as functions of wind speed and turbulence by first reducing pollen concentrations in the test room to zero by means of the bag filter and then measuring the rate of increase of pollen concentration in the room as the pollen penetrated from outside. This rate of increase is, of course, dependent on outside concentrations of pollen as well as on meteorological variables. These first tests were conducted in August and September of 1954 during the regular ragweed pollen season, and indicated that the methods, suitably modified, would be satisfactory.

It was then decided that some control of exterior concentrations would be advantageous. A pollen dispenser was therefore developed and used to bathe the test structure with pollen for short periods of time during the spring of the year when natural sources of ragweed pollen were absent. The external pollen distribution was monitored by a three-dimensional array of microscope slides on which pollen was impacted by the wind and later counted under the microscope. Pollen concentrations inside were measured as before. The results of one such test are given in Table I. Zero time in the table corresponds with the beginning of emission of

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TABLE I

Volumetric Pollen Counts in Test Room, May 16, 1955

Sample No.	Time (min.)	Pollen count	Average wind speed (mi./hr.)	Total gusts	Average ventilation rate k_3
1	0-3	94	3.8	37	0.866
2	3-6	25	3.4	43	0.654
3	6-9	12	3.6	43	0.642
4	9-12	6	4.0	64	0.897
5	12-15	1	4.7	70	0.420
6	15-18	1	4.8	64	

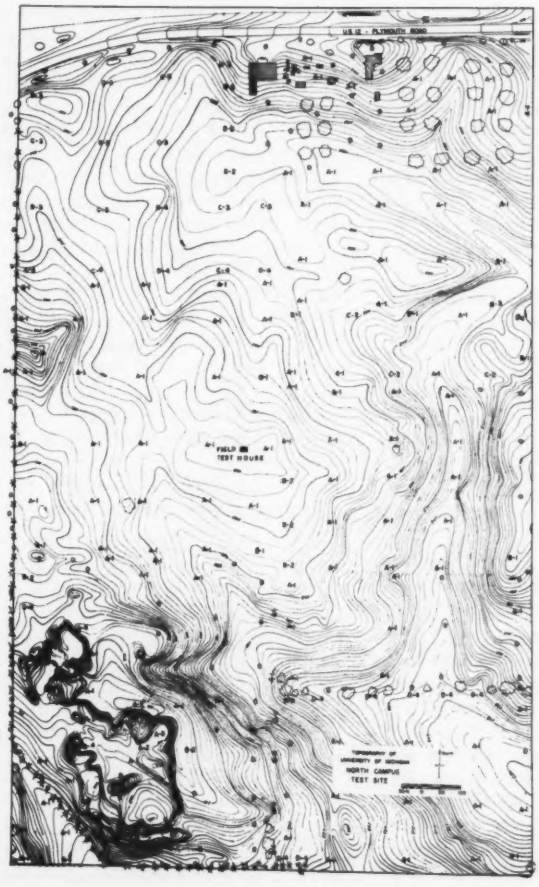
pollen by the dispenser, which lasted 1 min. 50 sec. Turbulence is represented by Total Gusts; this characterization of turbulence is described below. Average Ventilation Rate is defined as the number of air changes in the test room/unit time, in this paper/min. The last two values of the average ventilation rate are obviously questionable because the samples were too small for reliable results. The first three, however, are relatively firm values.

Full details of this preliminary experimentation have been given by Hewson and Dingle (1956); the distribution of pollen released from the dispenser shows features of considerable interest which will be published elsewhere.

Experimental Facilities and Procedures

Experience acquired in the experiments on the roof of the East Engineering Building suggested that the wind field over the roof-top test sites was so disturbed by local obstructions and general turbulence around the building that a new site should be located and equipped for the 1955 ragweed-pollen season. Upon inquiry it was discovered that the project could obtain the use of a construction field office from the Detroit contracting firm of Darin and Armstrong. A field site was chosen in an open meadow on University property adjacent to the North Campus. This meadow was planted with a hay crop which was harvested just prior to the ragweed-pollen season, so the relative absence of ragweed-pollen sources in the meadow itself was assured.

(i) The North Campus Field Site. —A topographic map of the area is shown in Fig. 1. Contours on this map are drawn at 1 ft. intervals. The symbols plotted are the result of a botanical survey and indicate the concentration of ragweed plants (*Ambrosia elatior*) according to the following scheme:
Abundance is an expression of the



(Left) Fig. 1. Topographic map of North Campus field site showing results of ragweed survey. Contours are drawn for 1 ft. intervals.

(Above) Fig. 2. The field test building on the North Campus.

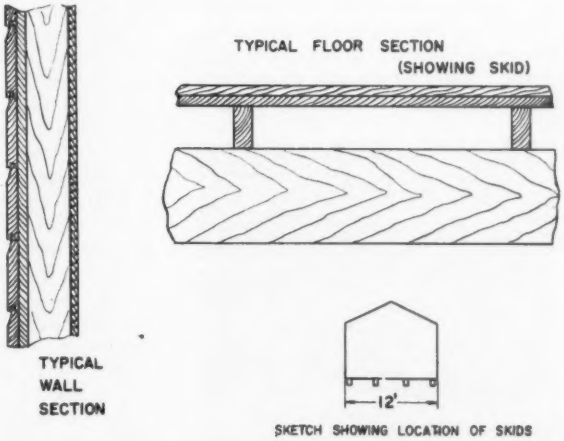


Fig. 3. Structural detail of field test building.

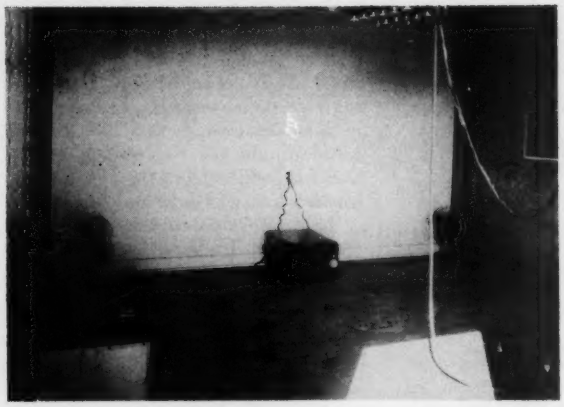


Fig. 4. Interior view of test room.

Fig. 5. Interior view of instrument room.

number of individual plants/m.^{2} in 4 classes:

A 1-10 plants/m.^{2}
B 11-20 plants/m.^{2}
C 21-30 plants/m.^{2}
D 31-40 plants/m.^{2}

Density is a measure of the proportion of space occupied by the ragweed plants, arrived at by visual estimate and coded in 4 classes:

(1) 1-25% cover
(2) 26-50% cover
(3) 51-75% cover
(4) 76-100% cover

The relative paucity of ragweed plants in the vicinity of the test site is evident from this map.

(ii) The Experimental Structure. —The test house is shown in Fig. 2. It is of frame construction, relatively well-built for a field-office type of building, and differing from conventional frame structures mostly in that it is built upon heavy skids and strengthened for portability. Structural characteristics are given in Fig. 3. Overall dimensions are 12 x 20 ft. The windows and doors are placed symmetrically in the west, south, and east-facing walls, the north wall having no openings. To provide suitable separation of the test-room portion (Fig. 4) and the instrument room (Fig. 5), a plywood partition was installed 8 ft. from the east end. The test room was therefore 12 ft. square in plan and 7 ft. high, with 1 window (double hung, 26 in. x 54 in.) in the west wall and 1 in the south wall, besides a door (34 in. x 80 in.) in the south wall.

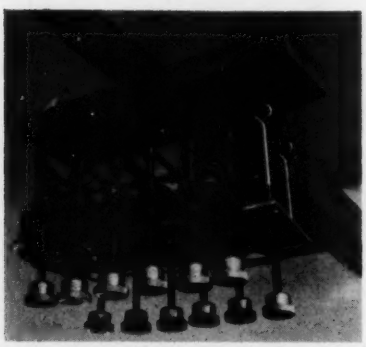


Fig. 6. Twelve-head sampling unit on scaffold outside field test building.

(iii) The Instrumentation. — The test room was equipped with 4 12-in. diam. oscillating fans, 1 in each corner and directed toward the center of the room, for the purpose of stirring the air thoroughly during all sampling runs. The simplicity of the room shape, absence of furniture, and intensity of stirring provided by the 4 fans combined to assure representative sampling.

Two electrostatic precipitators (Fig. 4) were used during the cleaning operation between tests. In addition, hand cleaning was done, and a vacuum sweeper was used. The samplers were hung in the center of the test room at a height of 6 ft. above the floor, as shown in Fig. 4. The outdoor air samplers were hung from a scaffold (Fig. 2) at a height of 7 ft. above the ground and about 8 ft. from the south wall of the test house. The Beckman-Whitley anemometer was erected nearby at a level of 8 ft. above the ground.

The electrical timers controlling the sampling valves and the pumps, the Beckman-Whitley wind-speed recorder, and the Eberbach pumps were housed in the instrument room (Fig. 5). In addition, this room contained facilities for mounting the millipore filters on microscope slides and a microscope with accessories for counting the samples obtained. Fig. 6 is a close view of the outside 12-head sampling unit in place; a cross section of the sampling head is shown in Fig. 7. The 12-head unit is an assembly of samplers connected to the air tube through individual solenoid valves. By means of the electrical control, the solenoid valves were opened one at a time for the desired sampling period. Simultaneity of sampling inside and outside the test room was obtained by connecting the respective inside and outside sampling valves in parallel to a 12-v. d-c supply through the timer.

(iv) The Experimental Procedure. —Before the beginning of each test, the test room was closed and cleaned thoroughly, using a vacuum cleaner. During the cleaning both the fans and the electrostatic precipitators were operated, and these were left in operation for at least 45 min. The test was then begun by shutting off the precipitators and starting the timing system and the wind-speed recorder. The timers were adjusted in advance to give the desired sampling periods and to shut off all electricity automatically after the completion of the test. Corresponding samplers outside and inside the test room were

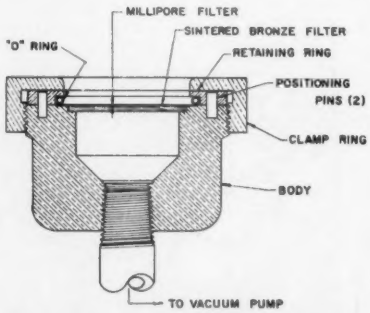


Fig. 7. Cross section of single sampler head.

operated simultaneously in all the tests.

Upon completion of a test, the filters were removed from the sampling heads and mounted on standard 1 x 3 in. microscope slides. The samples were protected with cover glasses and stored for later counting. In the counting operation, a 100-fold magnification was used and the entire area of each filter was examined.

The controlled variables in the experiments were *(1)* duration of individual sampling periods: 5 min., 10 min., and 15 min.; *(2)* window openings: none, 1 in., 3 in., and 12 in.; and *(3)* speed of rotation of stirring fans in test room: high, 1; medium, 2; and low, 3. Measured variables were: wind speed, which was recorded continuously during each test, using the Beckman-Whitley anemometer; wind direction, which was observed visually; the neighboring distribution of ragweed plants; and the pollen concentrations inside and outside the test room.

Preliminary Analysis

In analyzing data of this type, the first step was to reduce them to appropriate averages. This served the double purpose of summarizing the data in a condensed form and of smoothing variations which otherwise tend to mask the effects one wishes to observe. Such a summary of the field tests is presented in Table II. Note that in this table, conditions, both controlled and uncontrolled, vary between tests, so that care must be exercised in interpreting the figures.

A second step in the analysis is represented by Fig. 8, which shows graphically the relation of the ragweed pollen penetration rate as represented by the ratio x/m to the wind speed for nine tests in which the windows of the test room were closed. The tests plotted here are numbers 1-3, 9-11, and 17-19, inclusive, in Table II.

It is important, in this presentation, to use the ratio of the inside pollen counts x to the outside pollen counts m for a number of reasons. In the first place, these tests were made under natural conditions, that is to say, the level of atmospheric pollen concentration was entirely determined by natural variables. These include the mechanism whereby the pollen grains are released by the plants, the time and space distributions of turbulent eddies in the wind field, and the rate of mixing of the pollen grains through the air. The atmospheric concentrations of pollen were therefore highly variable throughout these tests. Secondly, the pollen concentrations inside the test room were dependent upon both the concentrations borne by the ventilation air and the rate of ventilation, both of which were dependent in one way or another upon the wind speed and air turbulence. The ratio of inside to outside concentrations provides a means for eliminating many of the detailed considerations of release and transport of the pollen grains and for reducing the problem to the direct consideration of ventilation and penetration.

Fig. 8 indicates that wind speeds below 6 mi./hr. were about uniformly effective for ventilating the closed test room, and that above 6 mi./hr. to the limit of the data (15.1 mi./hr.) the ratio x/m increased nearly linearly from 20% to nearly 100%. This particular finding is of considerable interest and merits further study.

TABLE II

Ragweed Pollen Penetration Tests, Summer, 1955

Test No.	Date 1955	Time Beg.	Time End	*Kind (see key)	Window opening (in.)	Fan speed	Avg. pollen count (no./sample) Outside	Avg. pollen count (no./sample) Inside	Avg. wind speed (mi./hr.)
1	8/20	9:30a.-	8:45p.	A	0	2	15.6	7.5	8.3
2	8/20-21	10:30p.-	9:45a.	A	0	2	36.6	6.4	5.2
3	8/21	12:00n.-	11:15p.	A	0	2	31.4	4.7	5.7
4	8/24	2:00p.-	3:05p.	B	12	2	89.9	40.2	3.6
5	8/24	4:30p.-	6:30p.	C	12	2	94.4	40.4	4.6
6	8/26	10:00a.-	11:00a.	B	3	2	53.5	14.5	3.3
7	8/26	2:00p.-	3:00p.	B	3	2	54.5	25.4	4.9
8	8/26	4:00p.-	5:00p.	B	3	2	50.3	13.3	3.2
9	8/30	2:50p.-	3:50p.	B	0	2	19.7	19.1	15.1
10	8/30	4:40p.-	5:40p.	B	0	2	10.5	7.2	13.5
11	8/30	6:30p.-	7:30p.	B	0	2	7.7	4.3	8.9
12	8/31	11:05a.-	12:05p.	B	1	2	31.4	24.0	9.9
13	8/31	1:00p.-	2:00p.	B	1	2	20.3	14.4	9.4
14	8/31	3:00p.-	4:00p.	B	1	2	23.9	12.4	9.7
15	8/31	4:45p.-	5:45p.	B	1	1	7.8	5.6	9.0
16	8/31	6:30p.-	7:30p.	B	1	3	5.7	4.2	6.6
17	9/1	12:06p.-	3:01p.	D	0	2	47.1	10.5	6.2
18	9/1	4:20p.-	7:15p.	D	0	2	38.0	5.8	4.1
19	9/1	8:00p.-	10:55p.	D	0	2	33.8	5.8	2.0
20	9/2	6:23a.-	9:18a.	D	1	2	29.3	3.8	1.9
21	9/2	9:50a.-	12:45p.	D	1	2	25.5	19.1	4.6
22	9/2	1:24p.-	4:19p.	D	1	2	27.2	9.3	4.9

*Kind of test, key:
A. 12 — 15-min. samples with 45-min. lapse between.
B. 12 — 5-min. samples with no time lapse between.
C. 12 — 10-min. samples with no time lapse between.
D. 12 — 10-min. samples with 5-min. lapse between.

Analysis of Wind Behavior

As indicated above, the behavior of the wind is fundamental to the processes of ventilation and penetration. On the one hand, the character of the wind determines the level of contamination of the outdoor air as regards pollen in this particular case. On the other, it is expected to influence the rate at which air enters the test room from outside and that at which air is removed from the test room.

The variability of the wind speed is a characteristic that appears pertinent to the problem at hand. One measure of this variability is the *total gustiness, G*, which is defined in terms of the number and magnitude of the fluctuations of the wind speed about the mean for the sampling period. Specifically, the definition

$$G = n_2 + n_3 + n_4 + n_5$$

was adopted. Here the subscripts designate the respective categories of wind speed variation (± 2, ± 3, ± 4, ± 5 mi./hr. relative to the period mean) and n is the number of gusts (accelerations and/or decelerations) in each of these categories. A typical wind trace is shown in Fig. 9, which also illustrates the method of obtaining the sampling period mean, v, the *gust count*, and the *total gustiness, G*. Fig. 10 shows the relation of G to v for all the 5-min. periods of the field experiment.

Pollen Penetration

The superficial studies of the ratios of inside to outside pollen concentrations serve to indicate that the penetration of pollen grains into the test room is related to wind speed and

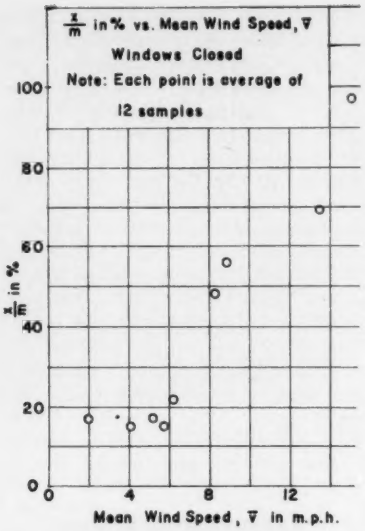


Fig. 8. Ratio of inside pollen count x to simultaneous outside pollen count m in relation to mean wind speed $\bar{v}$. Windows closed; each circle represents the average of 12 samples.

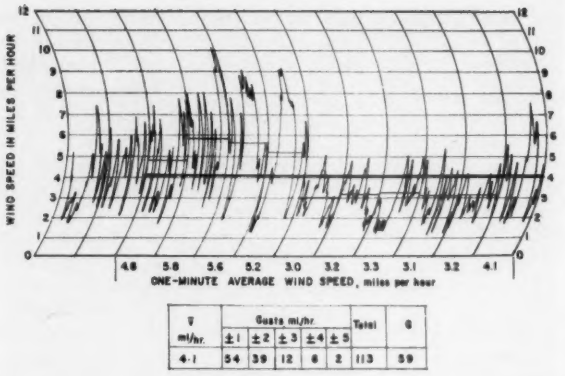


Fig. 9. Sample wind speed record and analysis. Test No. 18, Sample No. 5, 17:20-17:30, 1 Sept. 1955.

$\bar{V}$ mi/hr.	Gusts mi/hr. ±1	±2	±3	±4	±5	Total	G
4·1	54	39	12	6	2	113	59

gustiness. To develop the analysis further some considerations of the physical relationships involved are introduced.

It is anticipated that insofar as pollen grains penetrate into the test room, they do so by virtue of the exchange of air between the room and the outside. This means that the increase or decrease of the pollen concentration inside the room must be directly proportional to the difference between the concentration outside and that inside the room. The ventilation rate k expresses the rate of exchange of air between the atmosphere and the test room, in air changes/min., so again the change of pollen concentration in the room must be directly proportional to this ventilation rate.

(i) The Ventilation Rate, k.—The primary experimental factors affecting the value of k are: *(a)* the amount of crackage of the test room, *(b)* the amount of opening at the windows, and *(c)* the wind speed. A number of secondary factors may also be considered: *(d)* the degree of gustiness of the wind, *(e)* the wind direction and its variability, and *(f)* the speed of rotation of the fans in the test room. Of these factors, *(a)* is unknown, but usually assumed constant, and hence subject to deductive determination if other factors remain reasonably constant in a few cases; *(b)* is known and constant for each test, but varied from one test to another (see Table II); *(c)* is observed and reduced from the detailed wind-speed record; *(d)* is estimated statistically from the detailed wind-speed record; *(e)* is observed only occasionally and hence cannot enter the computations, but the omission of this factor from the initial calculations is justified by the findings of Georgii (1954), Warner (1940), and Wellner (1932) that wind direction is distinctly subordinate to wind speed in its effect upon ventilation rate; and *(f)* is known and constant for each test (see Table II).

(ii) The Relation of Wind Characteristics to the Ventilation Rate.—The relation of k to the wind speed was explored by constructing graphs (Figs. 11, 12, 13 and 14) of k vs $\bar{v}$ for each of several window openings. The subscript 1 indicates that these values of k were computed from tests in which the test room pollen concentrations remained constant. In Fig. 11, the data for tests 17, 18, and 19 (below 7 mi./hr.) are separated from those for tests 9, 10, and 11 (above 9 mi./hr.). The fact that the latter are much more broadly scattered than the former suggests that some factor other than just wind speed (such as increased instability near the ground) contributed to the scatter of points at the higher wind speeds. The present analysis is confined to wind-speed considerations because no adequate data on stability are available. Fig. 12 and 13 show better continuity of the population of points partly because the wind-speed ranges of these graphs are narrower than that of Fig. 11. The similarity of these graphs

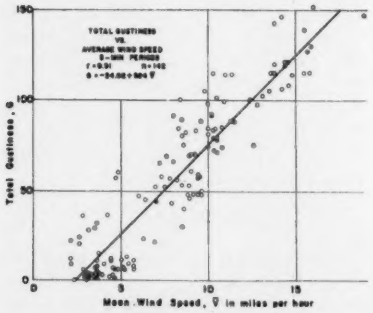


Fig. 10. Total gustiness G in relation to average wind speed $\bar{v}$.

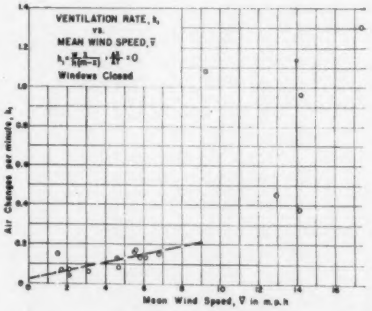


Fig. 11. Ventilation rate k_1 as a function of mean wind speed $\bar{v}$ for closed windows. The ventilation rate k_1 was computed from the equation given at the upper left, for x constant with time; w is falling speed of ragweed pollen, 3 ft./min.; and h is height of test room.

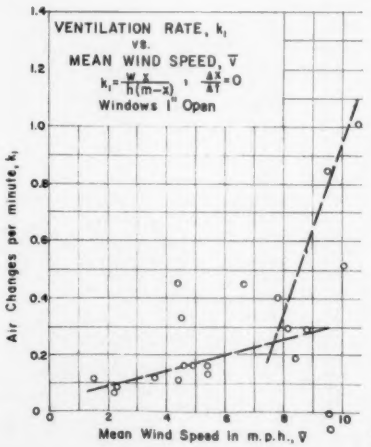


Fig. 12. Ventilation rate k_1 as a function of mean wind speed $\bar{v}$ for windows open 1 in.

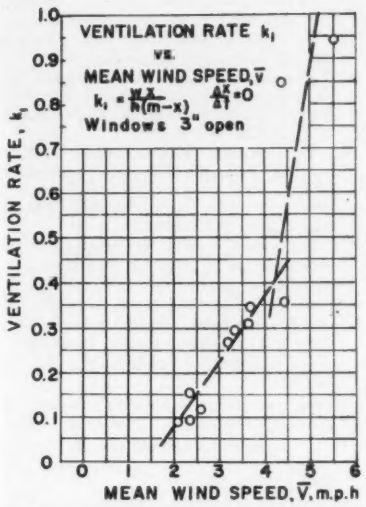


Fig. 13. Ventilation rate k_1 as a function of mean wind speed $\bar{v}$ for windows open 3 in.

to Fig. 8 indicates that the ratio x/m is a reasonably valid index of the ventilation.

Comparing Fig. 11, 12, 13, and 14, k_1 is seen to be an increasingly sensitive function of low wind speeds for progressively greater window openings. That is to say, the low wind speed portion of these graphs assumes increasing slopes as the window openings increase. The upper portions of the graphs appear to be somewhat less sensitive to the amount of window opening.

The possibility that there may be 2 different ventilation regimes is suggested by the 2 broken lines drawn roughly in Fig. 12 and 13. At low wind speeds there appears to be an approximately linear relation of k_1 to v, whereas at higher wind speeds a different and much steeper curve seems to relate the two. One interpretation of this distribution of points is that possibly the relation of k_1 to $\bar{v}$ is more properly a quadratic than a linear one.

Although there are not enough pairs of values of k_1 and $\bar{v}$ to make an adequate statistical evaluation of this possibility, there are many more values of the ratio x/m and, as indicated above, this ratio may be taken as an index of ventilation. Accordingly, least squares methods were used to fit quadratic equations to the data, x/m being expressed as a percentage and $\bar{v}$ in mi./hr., with the following results:

(a) windows closed, $n = 117$ sample pairs
$x/m = 16.69 + 1.39\,\bar{v} + 0.32\,\bar{v}^2$

(b) windows open 1 in., $n = 88$
$x/m = 4.26 + 14.45\,\bar{v} - 0.60\,\bar{v}^2$

(c) windows open 3 in., $n = 34$
$x/m = -23.56 + 20.31\,\bar{v} - 0.92\,\bar{v}^2$

The constant terms in these equations, taken with the coefficients of $\bar{v}$, are more properly to be considered indicative of the slope of the curve at low values of $\bar{v}$ than representative of a hypothetical value of x/m when $\bar{v} = 0$.

For case *(a)*, windows closed, the curve is as anticipated, its slope increasing with increasing values of $\bar{v}$. For the other two cases, windows open, the curvature is reversed and by virtue of the large coefficients of $\bar{v}$, the effect of $\bar{v}^2$ within the range of wind speeds encountered is quite small. This result suggests that linear equations are more appropriate for the range of wind speeds shown when the windows are open 1 in. or more. For the case when windows are closed, the $\bar{v}^2$ term begins to exceed the $\bar{v}$ term at about 4.5 mi./hr. and becomes increasingly important thereafter.

This analysis contrasts with the earlier one which seemed to suggest two wind regimes for each window opening (Fig. 12 and 13). The suggestion of the above equations is rather that the ventilation regime with windows closed is basically different from that with windows open. Physical reasoning supports this latter view. A dependence of ventilation on $\bar{v}^2$ is to be expected only when the wind is in effect stopped as by a solid object, so that the kinetic energy of the moving air, $\frac{1}{2}\,\rho v^2$, is transferred to the object and thus exerts a dynamic pressure on it, leading to increased pressures on its upwind face and to lowered pressures on its downwind face Air moves through cracks and chinks in response to such pressure differences but viscosity reduces the flow so much that the closed building acts effectively as a solid or slightly porous body. On the other hand, even with a window opening as small as 1 in., the air flow is relatively free through the room in comparison with the flow with windows closed, and the ventilation tends to approach proportionality to $\bar{v}$ rather than to $\bar{v}^2$.

It is of interest to compare this analysis with that of Georgii (1954), who found that ventilation of a closed room was given by an expression of the form $a + bv^2$.

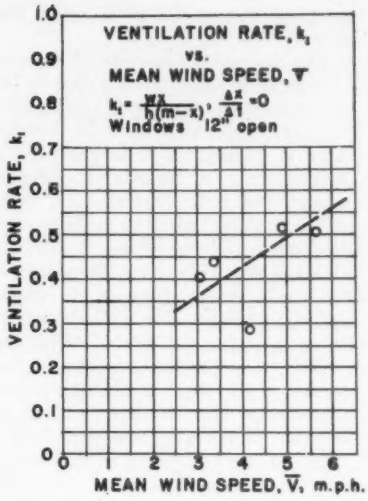


Fig. 14. Ventilation rate k_1 as a function of mean wind speed $\bar{v}$ for windows open 12 in.

Further analyses of the results of the present investigation will be published elsewhere.

Results and Conclusions

An experiment in which ragweed pollen were disseminated artificially outside the natural season for ragweed pollination was performed. On the basis of this experiment, 3-min. samples taken inside the test room showed a ventilation rate of the order of 0.6 to 0.7 air changes/min.

In field experimentation during the ragweed pollination season, the situation was much more complex, and evaluation of ventilation rates on the basis of pollen penetration data was less satisfactory. Ventilation rates computed from these data range between 0.04 and 3.87 air changes/min. under wind speeds ranging from 1.50 to 17.35 mi./hr. and with test conditions varying from windows closed to windows open 12 in.

Studies of the ventilation rate as a function of wind speed and window opening revealed several interesting functional relationships which should be examined in additional experiments and analysis.

Acknowledgments

We are pleased to acknowledge the assistance of a number of persons during the course of the research. Mr. William H. Hansen contributed greatly to the early development of the instrumentation employed, which was fabricated by Messrs. C. Samborski and K. L. Gleason. Mr. G. C. Gill assisted with the experimental

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Finally, we wish to express our deep appreciation of the generosity of Mr. John Armstrong, President of the construction company of Darin and Armstrong in Detroit. Mr. Armstrong supplied the field construction building used in the experiments on penetration at the North Campus site, arranged to have it delivered and set in place at the site, and then had it removed after completion of the experimental program, all without cost to the project.

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The Formation of Aerosols by Irradiation of Dilute Auto Exhaust*

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The possibility that considerable portion of the aerosols causing loss of visibility in Los Angeles County originate from photochemical reactions in the atmosphere[10] has received some experimental support. Haagen-Smit[7] has demonstrated that aerosols result from irradiation of mixtures of hexene, cyclohexene, or dicyclopentadiene and nitrogen dioxide at concentrations of a few parts per million in air. The same phenomenon could occur in the atmosphere because of the presence of hydrocarbons and oxides of nitrogen.

Auto exhaust is considered to be a major source of pollution in the Los Angeles basin at the present time. Another study is presently underway at these laboratories on the relationship between auto exhaust and eye irritation. Examination of the diluted exhausts offers a convenient method of determining whether aerosols form as a consequence of photochemical reactions which are induced to occur in this medium. The system also allows investigation of the dependence of aerosol formation on the composition of the dilute exhaust and the determination of some of the properties of the generated aerosol.

Equipment and Instrumentation

Preparation of Exhaust-Air Mixtures

The equipment used to prepare and irradiate a dilute mixture of auto exhaust and air for eye irritation studies has been described in detail in a previous report[14] and in a paper presented at this symposium [15]. Briefly, air is purified to a degree by combustion of all organics over a platinum catalyst and by filtration through a carbon filter. The purified air is mixed with the exhaust and forced through a 520 ft. irradiation chamber. After an average residence time of 1 hr. in the chamber, the mixture is analyzed for its eye irritating properties and for its content of hydrocarbon, carbon monoxide, nitrogen dioxide and nitric oxide. The controlled variables are the concentrations of four types of exhaust (idle, acceleration, cruise, and deceleration), relative humidity, temperature during irradiation (27 ± 2C), and light intensity (near ultraviolet which is comparable to noon sunlight on a winter day).

Aerosol Instrumentation

The aerosols in the exhaust-air mixtures were studied by means of two instruments: a counter photometer, which combines the functions of a recording light-scattering photometer and an electric particle counter [12,13], and a nuclei counter, which is a cloud chamber of variable expansion ratio combined with turbidimeter. The counter photometer differs from the previously described [12,13] instrument only in electronic circuitry.

The Counter Photometer

Description

When operating as a recording light-scattering photometer, the counter photometer records light in the wavelength region of 375 to 575 mμ. scattered into a conical solid angle 90° to the convergent incident illumination. The flowing aerosol which scatters light occupies the sensing volume previously defined[12,13]. This volume is 2.0 μl. as determined by the flow tube diam. (1.59 mm.) and the dimensions of the illuminating and viewing slits (2.0 x 1.0 mm.). (The scattering volume is 4.0 μl.)

When operating as a counter, the counter photometer sorts and counts the 1-millisecond voltage pulses at the photomultiplier anode caused by light scattered by individual particles of aerosol passing through the sensing volume. The pulses are classified into 11 classes according to height. It is usually necessary to dilute the aerosol sample with filtered air to avoid large coincidence errors.

Sampling, dilution, and flow through the counter are controlled by an aerosol flow system. The system used was based on the principles described by O'Konski *et al.*[12]. The advantages of this system are: *(1)* the aerosol is diluted with air which differs from the aerosol only in the absence of particulates, thus suppressing change of size due to condensation and/or evaporation, and *(2)* the sample streams are not passed through capillaries or orifices for metering, thus avoiding possible loss of aerosol in the flow meter.

Calibration

The counter photometer was calibrated with spray-dried dilute polystyrene latex hydrosol[12,13]. Table I shows the data obtained with three particle sizes. All signals are referred to photomultiplier anode currents and are *normalized* by division with the current due to light scattering by air in the scattering volume.

*Presented at the 132nd National Meeting of the American Chemical Society, September 8-13, 1957, New York, New York.

TABLE I.
Calibration Data

Latex Properties[a]				Calibration Data		
Dow Run No.	Diam. μ	Standard Deviation, %	Number of Measurements	Pulse Current,[b] A. x 10^9	Ratio of Pulse to Air-Scattering Current [c]	Standard Deviation, %[d]
LS-061-A	0.365	2.2	438	7.98 8.20	2.35 2.46	10.8 15.8
15-N-8	0.511	1.35	359	14.0 14.4	4.19 4.31	16.0 18.5
LS-066-A	0.814	1.35	357	32.5	9.74	18.0

a These data are furnished by Dow Chemical Company.

b The pulse currents are determined by comparing the response of the pulse sorting system to particles with the response of the pulse sorting system to a calibrated pulse generator.

c The use of air-scattering photocurrents to standardize instrument response is described in references [12] and [13]. The air-scattering current at the photomultiplier anode during the calibration was $3.3^4 \times 10^{-9}$.

d This standard deviation is based on particle size and not on pulse amplitude distribution. It is a direct measure of size resolution for this particular instrument at the time of calibration.

The data of columns 2 and 6 of Table I are closely approximated by the relationship $i_p/i_a = 13.8\ D^2 + 0.62$ where i_p = particule pulse current, i_a = air scattering photocurrent, and D = latex particle diam. in μ. The deviation from a simple proportionality to the diam. squared, found earlier[12,13] is probably due mostly to the characteristics of the pulse widener circuit used in this instrument. Extrapolation and interpolation of this relationship allow assignment of the class boundaries of the 11 counting channels of the instrument as shown in Table II.

The extrapolated value of the lower boundary of channel 1, 0.25 μ, was checked semiquantitatively by a test with 0.264-μ latex hydrosol. The statistical precision of the assigned boundaries varies from 1 to 5%, assuming validity of the fitted relationship. The least precise value is the lower boundary of channel 1. Deviation from the fitted relationship may occur at large particle sizes around 1 μ[12], which were not important in this investigation. Subsequent drifts were compensated by means of periodic checks with a calibrated pulse generator and by frequent measurement of the air-scattering signal.

The class intervals are somewhat smaller than justified by the resolution indicated by column 7 of Table I. This is because the sensitivity was increased to the limit set by a signal-to-noise ratio[12,13] near one for particles falling into channel 1.

This calibration enables the size distribution of an aerosol of unknown optical properties to be expressed as the size distribution of an equivalent polystyrene latex aerosol. Equivalence is in terms of light scattering under the conditions prevailing in the counter photometer. Diameters measured on this scale should be in proportion to true diameters, over a restricted range, in the case of particles which approximate dielectric spheres[6].

The photometric function of the instrument was roughly calibrated with the test aerosols of Table I. The result was $2i/i_a = (6.7 \pm 2.3) \times 10^{-2} \Sigma N_i D_i^2$. Here i is the photomultiplier anode current due to aerosol flowing through the sensing volume, and N_i is the number of particles of diam. D_i/ml. $i_a/2$ is one-half of the photomultiplier current due to air in the scattering volume of the instrument. (The ratio of scattering to sensing volume is approximately 2). Because of the large uncertainty at 95% confidence in the numerical coefficient of the above equation, it was decided to use the value 5.48×10^{-2} calculated from pulse duration and frequency assuming rectangular current pulses. This relationship is valid in form for any aerosol, provided the *diameters* are measured by light scattering using the latex calibration for, in a sense, this expresses only the relative relationship between the responses of the two functions of the counter photometer.

In addition to the sources of error discussed in references[12] and [13], there is an additional uncertainty of about 5% due to variations of flow rate through the instrument. The total uncertainty in photometric measurements is from 6 to 10%.

Nuclei Counter

The calibration used was that furnished by the manufacturer in the preliminary instruction manual. The size distributions obtained with this instrument are those of an equivalent aerosol of water droplets. Table III shows the diameter and supersaturations assigned to 5 positions of a piston determining the effective expansion volume. The supersaturations required to initiate condensation are of more immediate

TABLE II.
Assignment of Channel Boundaries

Channel No.	Boundaries, Diam. μ	Class Mark, Diam. μ	Class Interval, μ
1	0.251	0.295	0.088
2	0.339	0.388	0.097
3	0.436	0.482	0.091
4	0.527	0.568	0.082
5	0.609	0.662	0.106
6	0.715	0.758	0.086
7	0.801	0.890	0.178
8	0.979	1.066	0.174
9	1.153	1.242	0.177
10	1.330	1.420	0.179
Over-pulse	1.509		

TABLE III.
Calibration Data For Small Particle Detector

Detent Position	Particle Diameter Greater Than, μ	Relative Humidity for Condensation, %
1	0.2	101
2	0.04	106
3	0.012	122
4	0.0024	258
5	0.0016	400

Source: *Preliminary Instruction Book, Small Particle Detector Type C. N.*, GEI 44981, June 1955, General Engineering Laboratory, General Electric Company, New York.

interest, since in general, the true size of the particles will not correspond to the equivalent water aerosol.

Sampling

Counter Photometer

The sample was drawn through 1/4-in. copper tubing from the irradiation chamber to the intake jet of the counter dilution system. Flow rates varied between 25 and 250 ml./min. Since this study is concerned with relatively small particles of low inertia, no attempt was made to sample isokinetically.

When counts were made, the sample was diluted so as to accumulate a total of 2 to 6 thousand counts within a period of 5 to 10 min. The dilutions required ranged from 100 to 1,000-fold. A *blank* count was then made without sampling. The corrected total count/ml., obtained by subtracting the two rates and multiplying by an appropriate factor, has an estimated standard deviation ranging from 2 to 5% due to counting errors alone. Counts per milliliter into the various channels have larger counting errors which vary inversely as the square root of the count[2]. Coincidence errors ranged from 1 to 4%, and the counts were not corrected for them.

Nuclei Counter

Samples were drawn from a sampling port in the irradiation chamber wall through a Tygon tube to the instrument in the manner recommended by the manufacturer.

Experimental Procedure

The series of experiments designed to investigate the aerosol character of irradiated auto exhaust was started after considerable work had been done with a basic facility of the kind described in reference[15]. In fact, the aerosol study was introduced while a randomized set of experiments was being performed to discover the relationship between oxides of nitrogen, hydrocarbons, relative humidity, and eye irritation in irradiated exhaust mixtures. The design happens to be suited to a study of the dependence of aerosol formation on these same factors.

The 520-ft.^{3} chamber was used as a flow reactor. Dilute exhaust flowed through the chamber until concentrations of hydrocarbon and oxides of nitrogen had come close to their steady-state values. The mercury arcs were then turned on; within 2 to 3 hrs. the concentrations had come close to their new steady-tate values, and eye irritation measurements were made[15]. The light scattering from a continuously flowing sample of the chamber contents was recorded during each experiment. The continuity of the record was occasionally interrupted by a shift to the counting function of the instrument. Measurements of condensation nuclei concentrations were also carried out during each experiment.

Experimental Results

Light Scattering Data

Fig. 1 shows a typical light-scattering record obtained during the course of an experiment in which aerssol formation was found. The curves can be roughly characterized in an empirical manner by the 3 time periods and the 2 light-scattering increments indicated in Fig. 1. The increase in light scattering at steady state, Δ_s, was taken as a measure of the aerosol formed for each experiment. Table IV shows the experiments arranged according to concentration of oxides of nitrogen and concentration of deceleration exhaust. The corresponding increases in light scattering, Δ_s, and eye irritation index are also tabulated. Table IV includes some analytical data on oxides of nitrogen and hydrocarbons. These and other analytical data collected during these experiments are fully discussed elsewhere[14].

Table V lists values of the empirical parameters for the light-scattering record of each of the experiments of Table IV. In addition to these experiments a blank experiment was conducted on pure air alone. Light scattering remained constant within 20%. The variations noted were erratic and showed no correlation with irradiation.

Table VI shows the size classification by the particle counter approximately at steady state before and after irradiation of the exhaust mix-

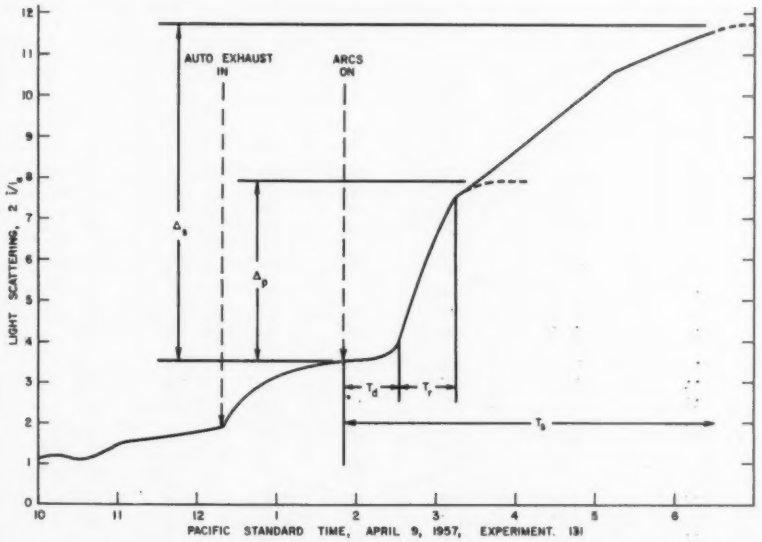


Fig. 1. Light-scattering Record During a Typical Experiment

TABLE IV.

Data Showing Dependence of Light Scattering and Eye Irritation On Exhaust Composition and Oxides of Nitrogen in Irradiated Mixtures With Pure Air

Experiment No.[a]	Relative Exhaust Composition by Vol.[b]				Nitrogen Oxides[c]		Hydrocarbons[d]		Relative Humidity	Increase in 90° Light Scattering[e]	Eye Irritation Index[f]
	Idle	Acceleration	Cruise	Deceleration	Before Irradiation, Ppm.	After Irradiation, Ppm.	Before Irradiation, Ppm.	After Irradiation, Ppm.			
146	0	0	0	9	0.37	0.22	9.2	6.9		3.3	3.2
130	1	0	18	0	0.53	0.63	1.0	0.9	78	0	1.6
131	1	0	18	4	0.60	0.52	3.8	2.7	42	6.5	11.2
143	1	0	18	6	0.65	0.45	4.6	3.1	65	9.2	4.8
137	1	0	18	9	0.70	0.42	8.1	6.1	55	10	8.8
136	1	4	18	6	0.45	0.34	3.6	3.0	72	7.8	6.8
142	1	4	18	0	1.2	0.83	0.9	0.8	38	0	1.6
133	1	4	18	4	1.2	0.75	2.5	1.9	55	3	6.8
140	1	4	18	9	0.98	0.67	8.5	6.1	65	30	15.2
145	1	8	18	0	1.2	1.17	0.9	0.8	66	0	2.0
144	1	8	18	4	0.90	0.73	2.6	2.0	78	2.0	4.4
141	1	4	18	6	1.2	0.75	4.4	3.2	53	14	12.8
139	1	5	18	0	1.8	1.97	1.0	1.0	55	0	2.4
132	1	8	18	9	2.0	0.91	7.1	4.8	42	26	14.4
134	1	15	18	4	(1.9)[g]	1.43	2.6	2.0	67	0	1.6
135	1	5	18	6	(2.0)	1.74	3.6	3.1	40	0.6	1.2
138	1	15	18	9	1.8	1.37	8.3	6.3	78	40	16.0

a Experiment number indicates temporal sequence.

b One unit corresponds to 71 ppm. of exhaust in the final mixture.

c Determined by a phenoldisulfonic acid procedure.

d Hydrocarbons were determined by absorption at 3.4 u and are expressed in terms of an equivalent concentration of n-hexane.

e Light scattering is expressed in multiples of the scattering from an equal volume of air at ambient temperature and pressure (approximately 25°C. and 750 mm. Hg.)

f Eye irritation was determined by a panel of 5 subjects. Four response classes were used, and the average over the entire panel was used to compute the index.

g Parentheses indicate values calculated from the exhaust composition.

(See Table V, next page)

TABLE VI.

Particle Counter Data Obtained During the Experiments of Table IV

Experiment No.	Class Mark, Channel 1, diam. μ	Before Irradiation					After Irradiation				
		Total per ml.	% in Channel				Total per ml.	% in Channel			
			1	2	3	4		1	2	3	4
146	0.31	120	71	20	4.5	1.4	200	73	19	3.8	1.8
130	0.29	210	67	24	4.8	2.0	160	73	18	4.0	2.1
131	0.29	220	60	26	5.9	2.6	550	75	19	3.3	1.3
143	0.30	100	69	18	5.0	3.2	190	80	13	3.0	1.2
137	0.30	250	68	22	5.7	2.0	490	75	18	3.2	1.4
136	0.30	170	68	24	3.0	2.2	290	76	18	3.2	1.4
142	0.31	100	73	22	0.7	2.5	NI	NI	NI	NI	NI
133	0.30	240	70	21	3.8	1.8	240	74	19	4.0	1.3
140	0.30	190	66	24	5.2	2.2	1170	80	17	1.8	0.6
145	0.31	100	64	23	5.4	2.9	82	62	26	5.1	2.8
144	0.31	120	65	23	4.8	2.6	100	70	20	4.2	2.4
141	0.31	230	62	24	6.4	3.6	360	80	15	2.0	0.8
139	0.30	190	63	25	6.0	2.5	110	67	22	5.6	2.6
132	0.29	220	73	17	4.4	1.9	1210	84	13	1.4	0.6
134	0.30	130	67	22	3.9	3.0	160	71	19	3.4	2.1
135	0.29	110	60	27	5.5	2.6	120	66	24	4.9	1.8
138	0.30	260	61	24	5.7	3.6	1810	80	16	1.8	0.8

NI = No information

TABLE V.

Empirical Parameters Characterizing the Light-Scattering Records Obtained During the Experiments of Table IV

Experiment Number	Time Parameters, in hrs.			Initial Light Scattering	Light-Scattering Increments	
	T_s[c]	T_d[a]	T_r[b]		Δ_p[d]	Δ_s[e]
146	2.4	0.08	0.44	3.7	2.5	3.3
130	N0	N0[f]	N0	3.8	N0	N0
131	>4.6	0.70	0.70	3.5	4.1	8
143	3.0	0.42	0.49	2.4	5.2	9.2
137	3.0	0.20	0.20	5.4	8.0	10.0
136	2.7	0.50	0.57	3.0	5.0	7.8
142	N0	N0	N0	2.1	N0	N0
133	>4	1.0	0.60	3.9	2.1	> 3
140	3.5	0.40	0.43	5.5	24	30
145	N0	N0	N0	1.8	N0	N0
144	N0	N0	N0	2.7	N0	N0
141	3.6	0.80	0.50	5.4	8.2	14
139	N0	N0	N0	4.2	N0	N0
132	3.3	0.25	0.36	3.7	10	26
134	N0	N0	N0	1.9	N0	N0
135	2.2	1.0	0.6	2.4	0.4	0.6
138	>2.5	0.73	0.84	6.2	32	>38

a T_d, illustrated in Fig. 1, is the time required after the arcs are turned on for the scattering increment to reach 10% of Δ_p.

b T_r, shown in Fig. 1, is the time elapsed between the 10% and 90% points of Δ_p.

c T_s is the time required after the arcs are turned on for the light scattering to reach its steady-state value.

d Δ_p is the light-scattering increment defined by 2 knees of the recorded curve (see Fig. 1).

e Δ_s is the final steady-state increment in light scattering (see Fig. 1).

f NO means not observed because no appreciable change in light scattering occurred during the course of the experiment.

ture. Only the first 4 channels are tabulated, because only in these channels were significant changes found.

Figs. 2 and 3 show the count frequency histograms for experiments 131 and 138. Although the percent of the particles counted in channels beyond channel 4 decreased on irradiation, the absolute number of counts/ml. of undiluted sample in these channels remained constant within the accuracy of the count. The diameter at the class mark of channel 1, given in Table VI, is a measure of the size classification at the time of the experiment. The diameter values of Table II should be adjusted proportionally to give class boundaries, marks, and intervals prevailing at the time of these experiments.

Condensation Nuclei Data

No consistent, significant change in the concentration of condensation nuclei at steady state was noted upon irradiation in all of these experiments. The major portion of the nuclei present before irradiation appears to come from the added auto exhaust. Typical concentrations are of the order of 10^4/ml. Of these, a fraction ranging from 50 to 90% required only 101% relative humidity to initiate condensation of water. More detailed data will not be given here because no special effort was made to obtain a representative sample of the aerosols in auto exhaust.

Although there was no net change in nuclei concentration on irradiation, an interesting transient change was noted in some experiments which also gave significant aerosol growth and eye irritation. (Significant data were not taken during all of the experiments because of experimental difficulties). It was observed that the nuclei concentration went through a transient peak at about the time or shortly before the initial rise in light scattering was taking place, *i.e.*, at the end of T_d of Table V and Fig: 1, or sometime during the early part of T_r. Fig. 4 shows smoothed data obtained during experiment 131, and Fig. 5, the data for experiment 132. The rapidity of the change precluded obtaining data at intermediate supersaturations.

Discussion

Irradiation of dilute auto exhaust can cause the appearance of aerosol particles of sufficient size and in sufficient numbers to increase light scattering by an appreciable amount. Table IV shows that, generally, increasing the amount of deceleration exhaust and, to a lesser degree, increasing the amount of oxides of nitrogen favor the formation of aerosol. Relative humidity had little or no effect within the range studied (38 to 78%).

Size Distribution

The shape of the size distribution histograms both before and after irradiation favors the hypothesis that most of the particles in these mixtures are below the counting range of the instrument. The sharpening of the peak in channel 1 caused by irradiation indicates that the particles so produced are small, and that probably the majority are below the counting range of the instrument. This hypothesis is supported by the results of calculating the fraction of the photometer reading due to countable aerosol shown in Table VII. The values of $2i/i_a$ are interpolated from the photometer chart to those times when the counting measurements were being made. The values of $\Sigma N_iD_i^2$ were calculated from the count data, using the class mark of each channel to represent the diam. of particles falling into that channel. The calculated percentages are subject to uncertainties due to error in the conversion factor for $\Sigma N_iD_i^2$, to losses upon dilution for counting, and to other errors. For these reasons the most significant changes are the large decreases in the % counted upon irradiation in those cases where a significant increase in light scattering was found.

The values of Table VII may be used in the relationship,

$$\sum N_i^A D_i^2 - \sum N_i^B D_i^2 < \frac{1}{k}$$

$$\left[\left(1 - \frac{P^A}{100}\right) \frac{2i}{i_a}^{-A} - \left(1 - \frac{P^B}{100}\right) \frac{i}{i_a}^{2-B} \right]$$

to obtain restrictions on the change in distribution of the smaller particle sizes caused by irradiation. Here, the superscripts A and B refer to after and before irradiation, P is % counted, k is the conversion factor

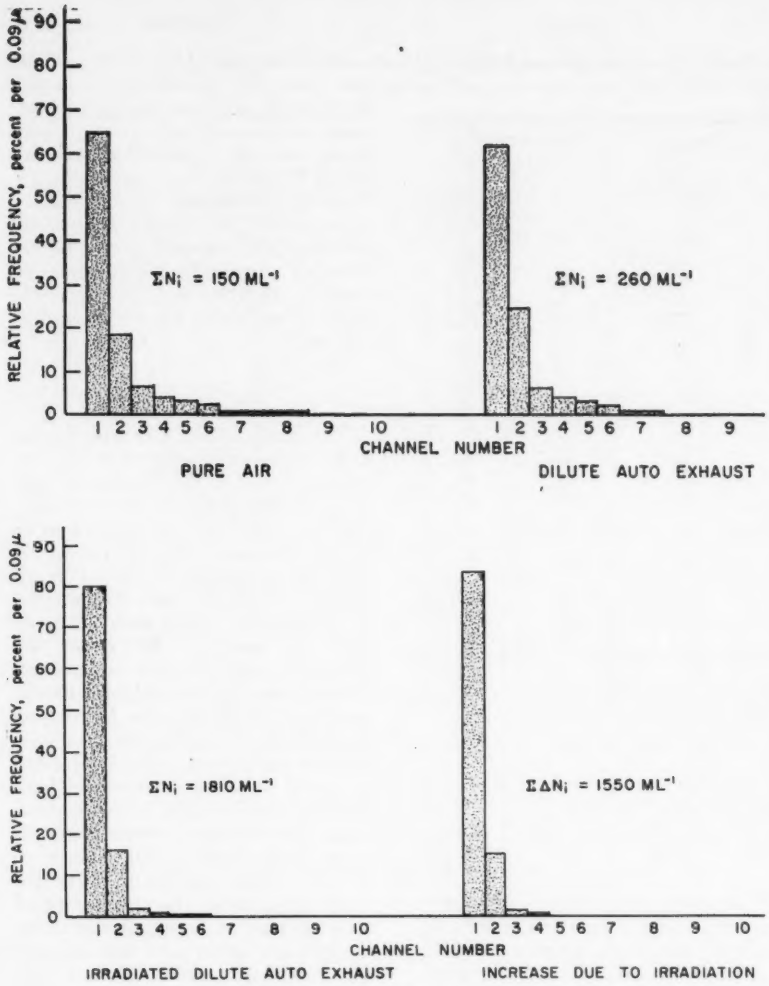


Fig. 2. Number Distribution, Experiment 131.

between $\Sigma N_i D_i^2$ and $2i/i_u$ (approximately 5.48×10^{-2}), and the summation is over all particles which are not counted. The diameters, D_i, are still on the scale established by polystyrene latex extrapolated beyond the lower end of the counting scale. For example, if it is assumed that the decrease in % counted is due to the appearance of 0.2 μ particles only then the lower bond on the number concentration of these particles may be calculated as 3×10^3 ml.$^{-1}$ for experiment 131 and 10×10^3 ml.$^{-1}$ for experiment 138.

The data on count distribution of the increase due to irradiation (see Figs. 2 and 3 and Table VI) in combination with the photometric data are consistent with the hypothesis that aerosol formed on irradiation is nearly monodisperse with an extrapolated mean diam. around 0.2 μ. The spread in diam. toward larger sizes shown in the count frequency histograms' (Figs. 2 and 3) could be mostly due to variation in pulse height caused by insufficient size resolution of the instrument (see column 7 of Table I). The discussion given below of other characteristics of the size distribution must be considered with this possibility in mind.

Mechanism of Growth

The source of the aerosol material or materials is evidently some secondary reaction or reactions in the photolysis of these mixtures. The generation of aerosol material in the primary photochemical act is not likely because of the nature of the products, *i.e.*, free radicals and excited molecules. Until further information can be obtained in the detailed mechanism of the photolysis and the chemical nature of the aerosol material, very little can be added to this conclusion.

The possible connection between aerosol formation and the transient peak observed in nuclei concentration needs further investigation. The increase in light scattering is much too small at the maximum of the transient peak of the larger nuclei to correspond to the number and size indicated. This suggests that the nuclei are hygroscopic. The rapid generation of aerosol material following an induction period might be an explanation of the above facts. The rate of generation is apparently sufficiently rapid to supersaturate to the self-nucleation point in spite of losses to chamber walls and growth on nuclei already present. The small particles generated by self-nucleation are identified in this model with the hygroscopic nuclei measured on the nuclei counter. The rate of deposition of material on nuclei initially present and coagulative processes accelerate with increasing size until steady state is achieved. The supersaturation is relieved and the self-nucleated particles disappear by process of mass transfer and coagulation with the growing larger particles. Such an explanation is consistent with most of the facts but involves many assumptions which are not supported by direct evidence. For example, self-nucleation may not actually take place; instead, it has been suggested[5] that the aerosol material in the gas phase may promote nucleation of water vapor in much the same manner as hydrochloric acid and other hygroscopic vapors promote nucleation of water vapor in diffusion cloud chambers[8,4].

Visibility Reduction

To obtain the visibility in an aerosol of nonabsorbing dielectric spheres from particle size distribution and number concentration, the volume scattering coefficient, β, must be calculated[11]. In the notation used here, $\beta \times 10^8 = \frac{\Pi}{4} \sum K_i D_i^2 N_i$ where β is in reciprocal centimeters and a ml. has been taken equal to 1 cm.^{3}. The scattering coefficient, K_i, is a function of the particle size and refractive index and of the wavelength of light in question. Its numerical values have been published in exten-

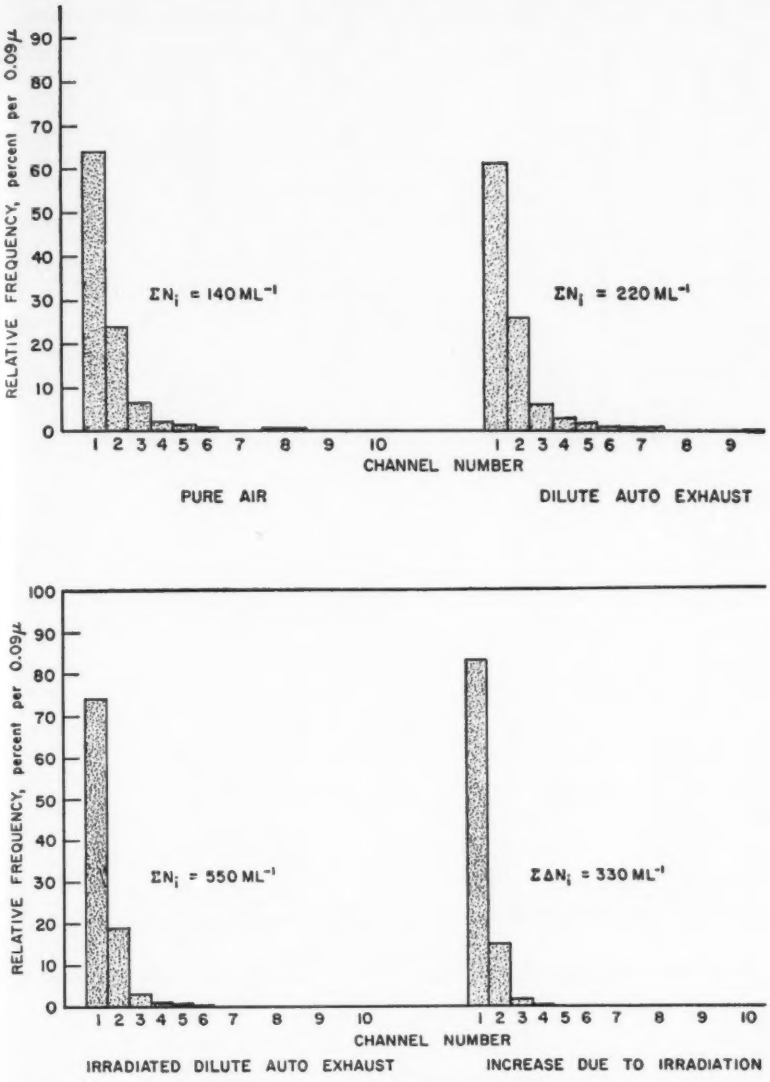


Fig. 3. Number Distribution, Experiment 138.

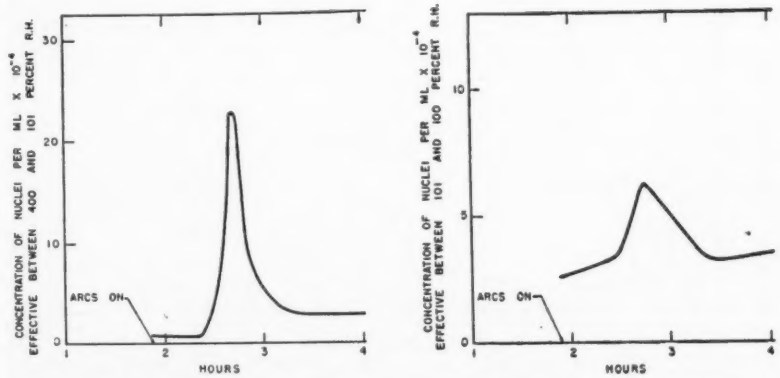

CONCENTRATION OF NUCLEI PER ML X 10⁻⁴ EFFECTIVE BETWEEN 400 AND 101 PERCENT R.H.
ARCS ON
HOURS
CONCENTRATION OF NUCLEI PER ML X 10⁻⁴ EFFECTIVE BETWEEN 101 AND 100 PERCENT R.H.
ARCS ON
HOURS

Fig. 4. Condensation Nuclei Transient Observed During Experiment 131.

sive tables by several groups. The visibility is calculated from the equation $v = -1/\beta \ (\ln \epsilon)$ cm. where Σ is the contrast limen, taken here is 0.02[17]. When the visibility is desired in miles, the equation becomes $2.44 \times 10^{-5}/\beta$ miles.

It is impossible to calculate the visibility reduction due to photolytic aerosol generation from dilute auto exhaust because of the present lack of precise data on the optical properties of the aerosol materials. The visibility corresponding to the equivalent polystyrene latex aerosol can be calculated as a rough approximation to show that the change in visibility is substantial. The increase in countable aerosol reduces the visibility calculated on this basis from 37 to 21 miles in experiment 131 and from 26 to 6.5 miles in experiment 138. The visibilities are further decreased by the aerosols not counted. If, for example, the uncounted aerosol is arbitrarily taken to be 0.2 μ in diam., then the visibilities are less than 32 and 15 miles for experiment 131, and less than 21 and 4 miles for experiment 138. These visibilities were calculated at 524 mμ for a refractive index of 1.65. The refractive index of polystyrene has been given as 1.625[9]. The values of the scattering coefficient were read from the curves given in reference[16]. There is some experimental evidence to indicate that the aerosols formed by irradiation had not completely *matured* at the time most of these data were taken, and that further aging would have increased particle size and decreased visibility still further.

It may be of interest to quote visibilities calculated for pure air to compare with the values obtained for dilute auto exhaust before irradiation. In experiment 131 the calculated visibility in pure air due to countable aerosol was 60 miles; if the smaller particles are taken into account by assuming 0.2 μ diam., then the visibility was less than 55 miles (% of photometer reading counted is 62). In experiment 138 the corresponding visibilities were 41 miles and less than 36 miles (% of photometer reading 57). The decrease in calculated visibility upon the addition of auto exhaust is not inconsistent with directly measured values of the attenuation coefficient of dilute auto exhaust[3], if the probable losses in the exhaust sampling

system and the errors of the method of calculation are considered.

Mass Distribution

The mass distribution of counted aerosol, based on the polystyrene latex scale, peaks in channel 1 for all aerosols encountered in these experiments. This is because the increase in number concentration in the lower channels more than offset the rapid decrease in particle mass with decreasing size. Figs. 6 and 7 show the mass distribution of countable aerosol using a density of one for experiments 131 and 138. Such calculated distributions are based on several arbitrary assumptions concerning the nature of the aerosol, and should be regarded as provisional and subject to drastic change as further data accumulate. Counting errors in combination with large mass/particle cause large fluctuations in the calculated values for the larger sizes. The distributions of the increase in mass due to irradiation are subject to less drastic assumptions concerning the aerosol, and are also shown in Figs. 6 and 7. The mass increments given in these figures are somewhat larger than the differences in mass before and after irradiation because those cases which would have yielded a decrease in mass for a channel were assigned zero change. Such negative values occurred only for the larger particle sizes where fluctuations due to errors could easily lead to falsely negative values.

Aerosols and Eye Irritation

The positive correlation between increase in light scattering and eye irritation in Table I is worthy of comment. The correlation naturally leads to the hypothesis that the aerosols formed are a cause of eye irritation or at least that they act synergistically [1,5]. Such a hypothesis is not proved by the data given here because a positive correlation is a necessary, but not a sufficient, condition for a causative relationship under the conditions of these experiments.

Conclusion

Aerosol can be formed by irridiation of dilute auto exhaust. Within the range of concentrations studied, aerosol formation is favored by increasing the concentration of deceleration exhaust, and, to a lesser degree, by increasing the concentration of oxides of nitrogen. The aerosol

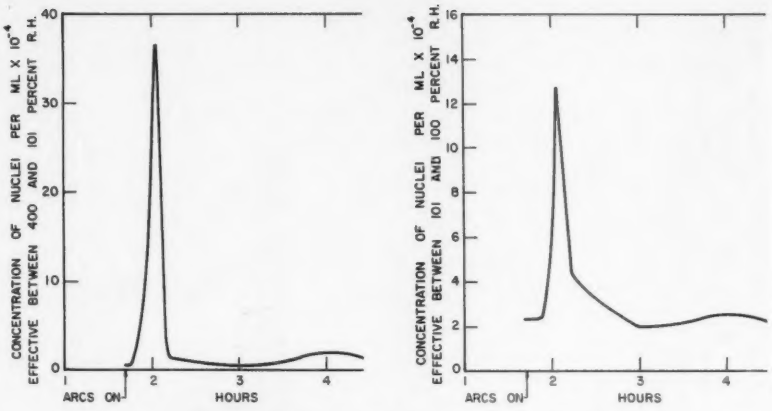
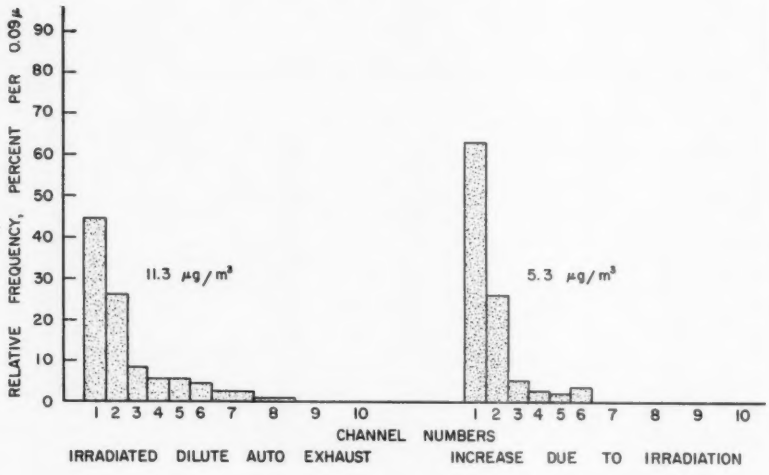

CONCENTRATION OF NUCLEI PER ML X 10⁻⁴ EFFECTIVE BETWEEN 400 AND 101 PERCENT R.H.
CONCENTRATION OF NUCLEI PER ML X 10⁻⁴ EFFECTIVE BETWEEN 101 AND 100 PERCENT R.H.
ARCS ON
HOURS

Fig. 5. Condensation Nuclei Transient Observed During Experiment 132.



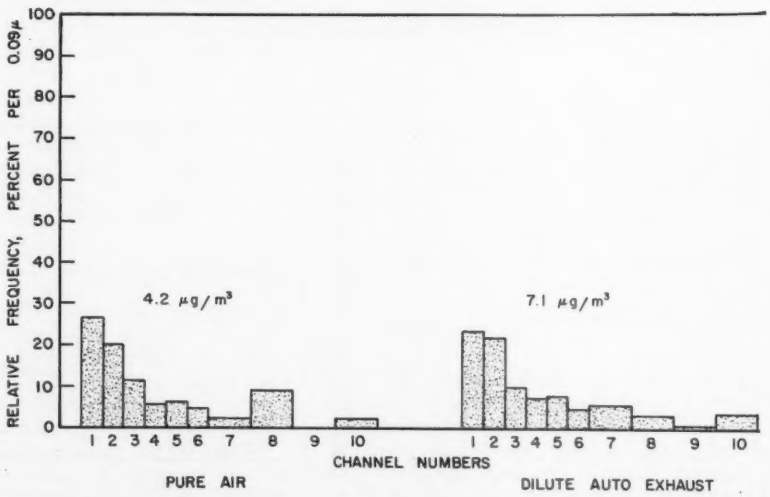


Fig. 6. Calculated Mass Distributions of Countable Aerosol, Experiment 131.

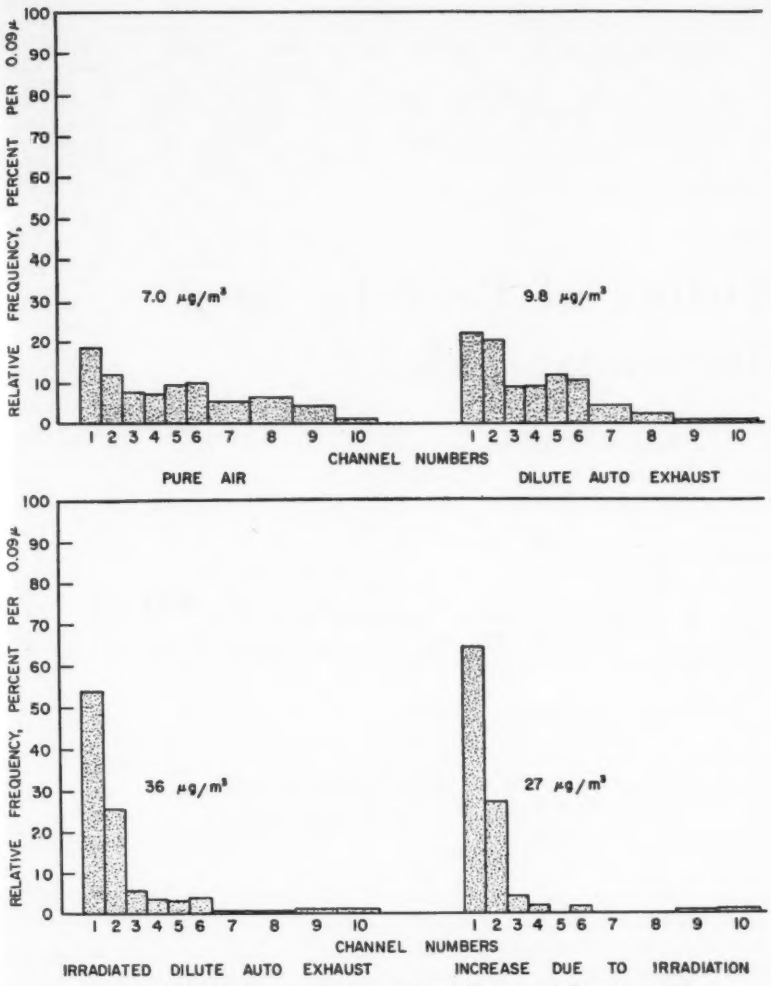


Fig. 7. Calculated Mass Distributions of Countable Aerosol, Experiment 138.

so formed is in the submicron size region but is of sufficient concentration and size to reduce visibility appreciably and to increase the mass concentration of aerosol. No connection between aerosols and eye irritation can be proved from the present data.

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TABLE VII.

Fraction of Photometer Readings Due to Counted Particles

Experiment No.	Before Irradiation			After Irradiation		
	$2i/i_a$	$\Sigma N_i D_i^2$	% Counted	$2i/i_a$	$\Sigma N_i D_i^2$	% Counted
146	4.1	16	21	6.4	25	22
130	3.3	26	43	2.9	20	38
131	3.5	29	46	11.0	49	24
143	2.3	15	36	8.2	23	15
137	5.4	31	31	13.6	57	23
136	3.5	22	34	9.4	34	20
142	2.3	14	32	1.4	.....	....
133	3.9	31	44	6.3	30	26
140	5.0	27	30	32.2	130	22
145	1.9	15	45	1.6	13	44
144	2.9	19	37	2.5	14	31
141	4.8	38	43	14.3	42	16
139	3.2	28	48	2.4	15	33
132	3.4	27	43	26.4	120	26
134	2.2	18	44	2.2	22	55
135	2.1	15	40	2.6	16	35
138	5.7	39	38	39.2	190	27

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Gravity Settling of Particles in a Horizontal Tube

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In sampling smoke and dust from incinerators, boiler stacks, *etc.*, it is frequently necessary to pass the smoke through horizontal lines. This raises the question of the amount of particle loss due to gravity settling therein. No direct solution of this problem could be found in the literature. The phenomenon of particle settling in horizontal lines is also of interest as a method of size separation. Use of horizontal sampling lines provides an extremely simple method for the determination of small particles only, since particles over a certain size will settle out before reaching the sampling filter.

The following calculations were made to establish F, the fraction of entering particles which are carried out of a horizontal tube of circular cross section, as a function of tube and particle parameters. It is assumed that a uniform concentration of particles of the same size and density enter the tube, that the particles are sufficiently small that they settle with a constant terminal velocity, that the horizontal velocity of the particles is the same as the horizontal air stream velocity at any point, and that streamline flow conditions exist in the tube. The following tube and particle parameters are involved:

V_{av} = average air velocity in tube, ft./min. (the volume of air per min. entering, Q, divided by the cross-sectional area of the tube)

Z = settling velocity of particle under gravity, ft./min.

L = horizontal length of tube, ft.

R = radius of tube, ft.

T = time, min.

Figure 1 shows the situation at a distance L down the tube. The origin of coordinates is taken at the axis of the tube.

After moving a horizontal distance L, the particles in the upper part of the tube will have settled away from the upper circumference of the tube, and there will exist a boundary line between an empty area and the remainder of the tube still containing particles. We let T= 0 at the entrance to the tube, and consider the case of a particle entering anywhere on the upper circumference of the tube at a distance x from tube axis. At some later time T the particle will have fallen vertically a distance ZT, arriving at the position (x, y) where

$$(1) \qquad y = \sqrt{R^2 - x^2} - ZT$$

During this time the particle will have traveled a distance L forward in a horizontal direction, given by

$$(2) \qquad L = \int_{T=0}^{T=T_1} \vec{V}\, dt$$

where $\vec{V}$ is the horizontal air velocity at all particle positions. For streamline flow, $\vec{V}$ is given by[1]

$$(3) \qquad \vec{V} = \frac{2 V_{av}}{R^2}\left(R^2 - r^2\right)$$

(1) O'Brien and Hickok, *Applied Fluid Mechanics*, p. 90. McGraw-Hill, New York (1937).

Also, from Fig. 1,

$$(4) \qquad r^2 = x^2 + \left(\sqrt{R^2 - x^2} - ZT\right)^2$$

Substitution of *(3)* and *(4)* into *(2)* gives

$$(5) \qquad L = \int_0^{T_1} \frac{2 V_a}{R^2}\left(2 ZT\sqrt{R^2 - x^2} - Z^2T^2\right) dT$$

The limit T_1 is the time the particle required to reach the position (x, y) and is

$$(6) \qquad T_1 = \frac{\sqrt{R^2 - x^2} - y}{Z}$$

Integration of (5) and substitution of the limits gives

$$(7) \qquad L = \frac{2 V_a}{3 R^2 Z}\left(2\sqrt{R - x^2} + y\right)\left(\sqrt{R^2 - x^2} - y\right)^2$$

Equation *(7)* is that of the boundary line dividing the denuded area from the area containing particles, at a distance L down the tube. Fig. 2 shows a plot of the equation for various L with the following quantities constant:

R = 0.215 in. = 0.0180 ft.
Z = 0.15 ft./min. (5μ dia. particle, density 1)
Q = 0.0119 cfm.
$V_a = \dfrac{0.0119}{\pi\,(0.0180)^2} = 11.7$ ft./min.

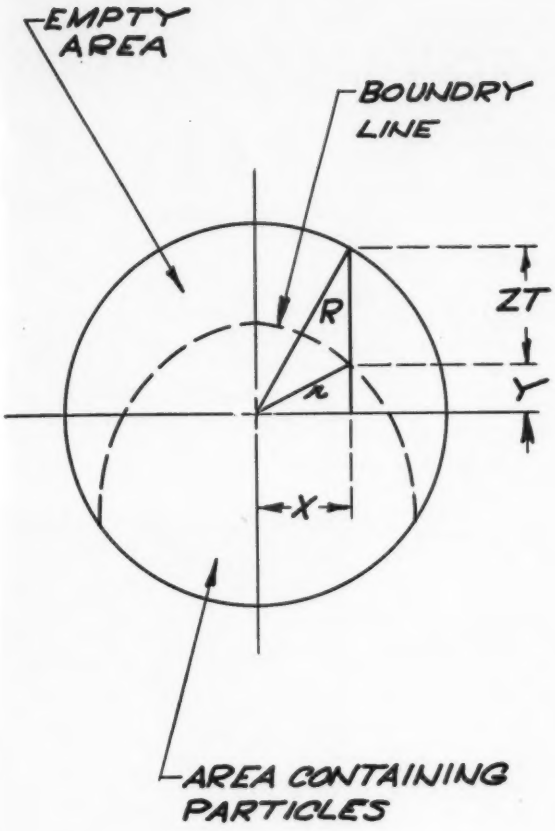
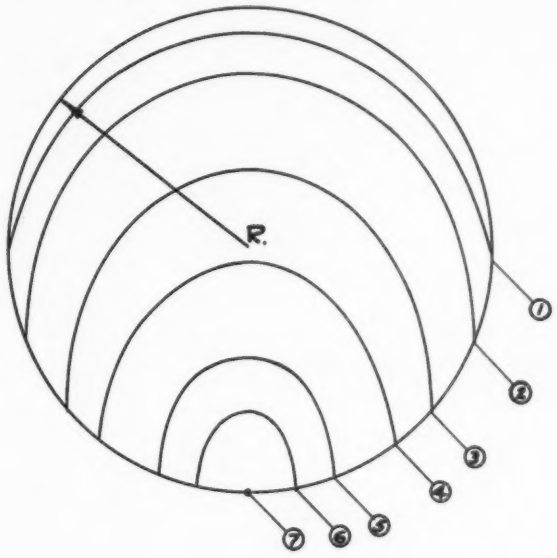


Fig. 1. (left)

Fig. 2. Particle Settling in a Horizontal Tube.

1—L = 0.03 ft.	6—L = 3.5 ft.
2—L = 0.2 ft.	7—L = 3.75 ft.
3—L = 1.0 ft.	R = 0.0180 ft.
4—L = 2.0 ft.	Z = 0.15 ft./min.
5—L = 3.0 ft.	Q = 0.019 cfm.



The particle starting at x = 0 (on the upper circumference) will travel the greatest distance L before settling out. When it contacts the bottom of the tube, y = —R. Substituting these values into *(7)*, there is obtained

$$(8) \quad L = \frac{8\,V_a\,R}{3\,Z} = \frac{8\,Q}{3\,\pi\,Z\,R}$$

Equation *(8)* defines the length L of a tube of radius R, just necessary to settle out all particles with settling velocity Z, for values of Q in the streamline flow region. All particles having settling velocities of Z or higher will settle out in the tube.

Calculation of F

The fraction of influent particles which do not deposit out in passage through the tube, F, may be found by use of the boundary line equation. At any distance L the area above the boundary line is empty of particles, and the area below is filled with particles. The number of particles/cm³. in the filled area is the same as the number/cm³. at the entrance of the tube, since it is assumed that all fall at the same rate Z, and there exists a constant input of particles into the entrance.

The ratio of particles not depositing in the tube to total particles entering is therefore given by the ratio of the volume of air flowing/min. below the boundary line to the total volume entering, or

$$(9) \quad F = \frac{Q_c}{Q}$$

where Q_c is the volume of air emerging/min. below the boundary line, and Q is the total flow rate. The conditions (see sketch) are symmetrical with respect to x. F is found as follows:

$$(10) \quad F = \frac{2}{Q}\int_{x_1}^{x_2}\int_{y_1}^{y_2}\vec{V}\,dy\,dx$$

Substituting $Q = \pi R^2 V_{av}$ and $\vec{V}$ from equation *(3)* there is obtained

(11)

$$F = \frac{4}{\pi R^4}\int_{x_1}^{x_2}\int_{y_1}^{y_2}(R^2 - x^2 - y^2)\,dy\,dx$$

Integrating with respect to y,

(12)

$$F = \frac{4}{\pi R^4}\int_{x_1}^{x_2}\left[(R^2 - x^2)\,y - \frac{y^3}{3}\right]_{y_1}^{y_2}dx$$

The upper limit y_2 is given by the boundary line curve, equation *(7)*. This equation could not be solved explicitly for y in terms of x. However, from equation *(7)* we have

$$(13) \quad (R^2 - x^2)\,y_2 - \frac{y_2^3}{3} = \frac{2}{3}(R^2 - x^2)^{\frac{3}{2}} - \frac{L\,R^2\,Z}{2\,V_a}$$

Since the left hand side of *(13)* is exactly the term in the brackets of *(12)*, the value of the substituted upper limt y_2 is

(14) $$\frac{2}{3}(R^2 - x^2)^{\frac{3}{2}} - \frac{L R^2 Z}{2 V_a}$$

The lower limit y_1 is defined by the lower circumference of the circle,

(15) $$y_1 = -\sqrt{R^2 - x^2}$$

Substitution of these values into *(12)* gives

(16) $$F = \frac{4}{\pi R^4}\int_{x_1}^{x_2} \left(\frac{4}{3}(R^2 - x^2)^{\frac{3}{2}} - \frac{L R^2 Z}{2 V_a}\right) dx$$

Integrating,

(17) $$F = \frac{4}{3\pi R^4}\left[x (R^2 - x^2)^{\frac{3}{2}} + \frac{3}{2} R^2 x (R^2 - x^2)^{\frac{1}{2}} + \frac{3 R^4}{2}\sin^{-1}\frac{x}{R} - \frac{3 L R^2 Z x}{2 V_a}\right]_{x_1}^{x_2}$$

The limit x_1 is 0; the limit x_2 is the x intercept of the boundary line on the the circle, which is designated x_c. The value of x_c may be found from equation *(7)*. At the intersection of the boundary line with the circumference of the circle,

(18) $$x_c^2 + (-y_c)^2 = R^2$$

Substitution of *(18)* into *(7)* gives

(19) $$x_c = \sqrt{R^2 - \left(\frac{3 L R^2 Z}{8 V_a}\right)^{\frac{2}{3}}}$$

and

(20)

$$-y_c = \sqrt{R^2 - x_c^2} = \left(\frac{3 L R^2 Z}{8 V_a}\right)^{\frac{1}{3}}$$

Also the following relation exists:

(21)

$$\frac{3 L R^2 Z x_c}{2 V_a} = \left(\frac{3 L R^2 Z}{8 V_a}\right)\left(4 x_c\right) = -4 x_c y_c^3$$

Substituting in the limits x_c and 0 in *(17)* and using equations *(20)* and *(21)*, there is obtained

(22)

$$F = \frac{4}{3\pi R^4}\left(-x_c y_c^3 - \frac{3}{2} R^2 x_c y_c + \frac{3 R^4}{2}\sin^{-1}\frac{x_c}{R} + 4 x_c y_c^3\right)$$

Collecting similar terms and simplifying,

(23)

$$F = \frac{2}{\pi}\left(\frac{2 x_c y_c^3}{R^4} + \sin^{-1}\frac{x_c}{R} - \frac{x_c y_c}{R^2}\right)$$

An algebracially equivalent form in dimensionless parameters is:

(24)

$$F = \frac{2}{\pi}\left(\alpha\beta + \sin^{-1}\beta - 2\alpha^3\beta\right)$$

where

(25) $$\alpha = \left(\frac{3 L Z}{8 V_a R}\right)^{\frac{1}{3}}$$

$$\beta = \sqrt{1 - \alpha^2}$$

Equations *(24)* and *(25)* give a complete solution to the problem.

APCA's
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Dust Retention Efficiencies of Dustfall Collectors*

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Dustfall collection involves the use of containers often accommodating a small amount of liquid into which particles drop from the atmosphere. The wetting action of the liquid is intended to entrap the dust fall-out and prevents its re-entrainment by wind

Fig. 1.

action. Water is customarily used because it readily permits subsequent analysis of the dust content. To retain effectiveness of water entrainment, it becomes necessary either to add anti-freeze in cold weather or to replace evaporation losses in warm weather.

Since dustfall collection usually involves a relatively large number of sampling sites scattered over a community area, an appreciable amount of time is required in visiting the sites to replenish the collectors with anti-freeze or water. Polyethylene containers require this attention only on the assumption that a wet bottom collector is superior to a dry bottom collector in dustfall retention. Collectors made of glass or other fragile material further require anti-freeze to prevent fracture by water freezing.

Presented at Golden Jubilee Meeting of the Air Pollution Control Association held June 2-6, 1957, St. Louis, Missouri.

If the assumed superiority of the wet container should be insignificant, the time spent in servicing to maintain the liquid could be saved by using dry flexible collectors. Accordingly, this study was undertaken to investigate whether dry collection techniques which overcome the disadvantages of wet collection possess an equally high dust retention efficiency. One technique tested involves the use of a baffle designed to fit in the collector and prevent the formation of wind vortices that might tend to sweep out the dust. The performance of dry collectors with and without baffles was evaluated in terms of their dust retention as compared to that of unbaffled wet collectors exposed simultaneously to the same field conditions. In addition to the relative efficiencies of dust retention, the performance test was designed to

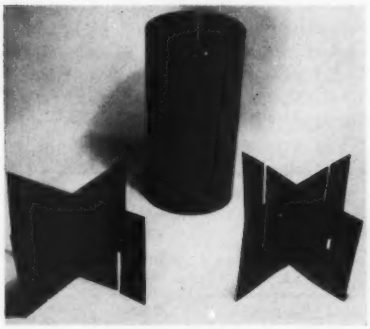

Fig. 2.

measure the absolute efficiency of each type of collector by "spiking" with a known weight of dust of such magnitude that the actual fall-out would be negligible in comparison.

Test Experiment

An experiment was designed to evaluate the performance of the three types of collectors by simultaneous exposure to actual field conditions. It was set up on the roof of a seven-story laboratory building located in a residential area adjacent to some industry. The collectors were directly subject to winds from all sides excepting one which had a hillside overlooking the building. The experiment was conducted for 5 weeks in the fall and repeated in early spring. Each period included a number of days of rain which temporarily converted all the containers to wet collectors. A similar experiment is scheduled to be performed at the Southwest Research Institute in San Antonio, Texas, where extended periods of dry exposure can be maintained.

The polyethylene container used throughout the study was cylindrical with a slight taper from top to bottom (Fig. 1), 10¾ in. in height and an opening diam. of 7¾ in. The baffle used was constructed (Fig. 2 and 3) of vinylite plastic sheet (0.9 mm. thick) and designed to match the taper of the container in such manner as to be clear of the bottom by about 2 in. and flush with the top.

Wooden racks were used to prevent the collectors from being overturned or blown away by heavy winds. Initially, the racks did not

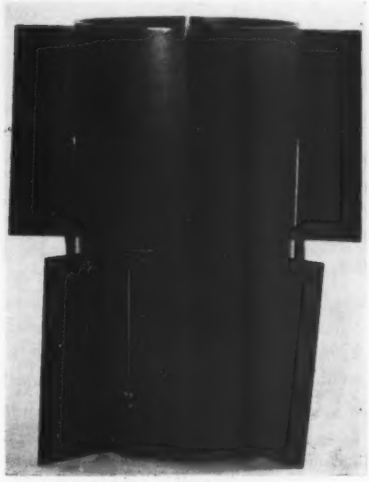

Fig. 3.

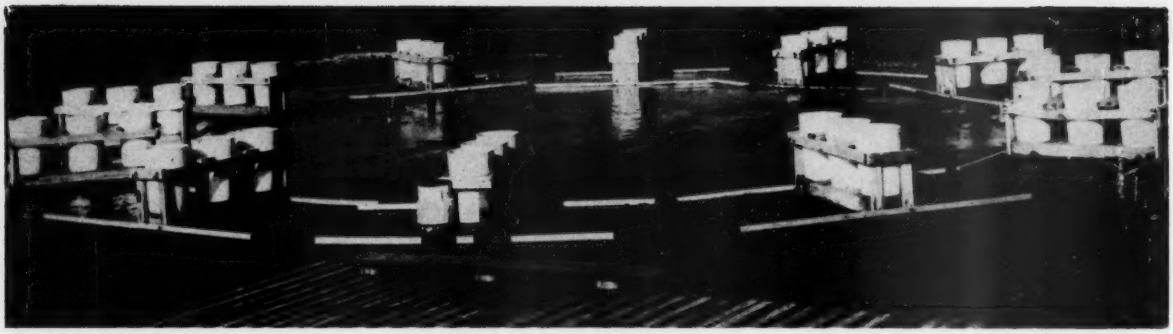

Fig. 4.

have the wooden braces on the bottom and several were overturned. Each rack accommodated a set of 3 containers (Fig. 1) which represented each type being studied, namely, dry-bottom collection, wet-bottom collection, and dry-bottom collection with baffle. For statistical reasons, 12 of these sets were arranged in a circular pattern (Fig. 4) with the types of collectors randomly ordered within sets, a total of 36 containers. This arrangement allowed a statistical evaluation of bias on any set as a result of local meteorological effects near the edge of the roof.

Six of the sets were spiked with 5 gr. of Fine Air Cleaner Test Dust and the remaining 6 sets were left unspiked. The spiked and unspiked sets alternated in the circular arrangement. The wet-bottom collectors were set up initially with 500 ml. of distilled water and were maintained wet with subsequent additions. During freezing conditions, ethyl alcohol was added as an anti-freeze. The dry-bottom collectors were not necessarily kept dry, but were subject to the existing weather.

Gravimetric Analysis

Preliminary to the gravimetric analysis, the contents of each collector were screened for extraneous material, using a 20 mesh screen**. In both experiments the suspended solids were separated from the dissolved solids by filtration of the contents of the unspiked collector through a "Millipore" filter (type HA, 47 mm. diam.). The filtrate evaporated to partial dryness and the filtered solids were each dried to constant weight in an oven at 104°C. The measured net weight of the dissolved solids was combined with that of the suspended solids to give the total weight of solids.

In the case of the spiked collectors, a partial separation was made by centrifugation. A small amount by weight, consisting of very fine dust remained in the supernatant liquid. Since filtration of the supernatant liquid through a Millipore filter would be extremely slow because of the clogging properties of this fine suspension, the supernatant was not filtered but was taken to dryness in the same manner as the filtrate from the unspiked samples. In the spring trial, no attempt at separation was made and total solids for the spiked samples was determined by the direct evaporation procedure. Controls, consisting of two spiked collectors unexposed to atmospheric dustfall or wind action, were analyzed simultaneously to evaluate the efficiency of the procedure.

Fungus growth was mainly responsible in retarding filtration through the Millipore filter. Dry dust taken up in water just previous to filtration did not present the same problem. In the first experiment quaternary ammonium chloride was used as an algae inhibitor in an amount of 1 ppm. by weight based on the anticipated maximum volume of water (1*l*.) that would be received in the collectors as a result of accumulated rainfall. The inhibitor was ineffective against fungus and some algae growth. In the second experiment, 0.5 ppm. by weight of mercuric chloride was added but at this low concentration proved unsatisfactory.

Dustfall Retention

The difficulty encountered in the gravimetric analysis as a result of organic growth in the collectors presents a number of problems that warrant a separate investigation. If such growth is tolerated on the basis that no separation of solids is required, then there is a question of the gravimetric effects of such matter relative to actual dustfall. On the other hand, to suppress the growth, it will be necessary to select and apply a chemical that will serve as an appropriate toxicant to both algae and fungus when used at concentrations that would not be a health hazard if inadvertently consumed by humans or animals.

TABLE I

Dustfall Analysis Data

Collectors	Experiment 1			
	Unspiked		Spiked	
	Mean Wt. Mg.	Std. Dev. %	Mean Wt. G.	Std. Dev. %
Dry	114.	14	5.12	0.9
Wet	124.	12	5.05	1.5
Baffle	113.	5	5.06	0.9
Collectors	**Experiment 2**			
	Unspiked		Spiked	
	Mean Wt. Mg.	Std. Dev. %	Mean Wt. G.	Std. Dev. %
Dry	161	15	4.94	1.5
Wet	158	28	4.88	0.9
Baffle	167	7	4.92	3.6

** Recommended Standard Methods for Continuing Dustfall Survey (APM 1-a) Air Pollution Control Association, Committee on Air Pollution Measurements.

TABLE II

Dust Retention Efficiencies

Collectors	Experiment 1			
	Unspiked		Spiked	
	Mean Eff. %	Std. Dev.	Mean Eff. %	Std. Dev.
Dry	91.	4.	100.	0.9
Wet	100.	—	99.	1.5
Baffle	92.	15.	99.	0.9
Collectors	Experiment 2			
	Unspiked		Spiked	
	Mean Eff. %	Std. Dev.	Mean Eff. %	Std. Dev.
Dry	112.	45.	99.	1.5
Wet	100.	—	98.	0.8
Baffle	111.	22.	99.	3.4

In the first experiment the loss of 2 sets each of the spiked and unspiked collectors due to high winds reduced the number of samples for analysis to 4 sets of each type. In the second experiment, however, the initial 6 sets of each type remained intact, providing data on all 36 collectors.

A statistical evaluation was made of the results of the gravimetric analysis (Table I). The weights of dust from a set of collectors of a given type are averaged to give a mean value. The standard deviation is expressed as a percentage of the mean.

The unspiked collectors, although limited in number, show a large percentage standard deviation primarily because they were sampling a dustfall which was light and random. The dry collector with a baffle, however, has a significantly lower deviation showing that the baffle tended to level out the random effects in sampling. This would indicate that individual sampling using a baffled collector will tend to be more representative statistically of the population mean.

In the spiked collectors, the dustfall contribution is a small percentage of the total dust involved and the random effects of sampling are expected to contribute little to the deviation values. This is verified by the markedly lower percentage deviation values as compared to those for the unspiked collectors. When the mean values in both spiked and unspiked sets are compared and examined statistically, the result shows that there are no significant differences in the amounts of dust retained in the 3 types of collectors.

Retention Efficiency

The efficiency of dust retention was calculated for each type of collector separately: in the unspiked collectors, it is the relative percentage ratio of the weight of dust in the baffled or unbaffled dry collector to that in the wet collector of the same set; in the spiked collectors, it is the absolute percentage ratio of the weight of dust in each collector to the composite weight of dust, consisting of the spiked dust and the dustfall given by the average mean weight of dust of the unspiked collectors. The relative and absolute percent efficiencies for a set of collectors of a given type were averaged to give corresponding mean values (Table II). The standard deviation is expressed as the difference from the mean.

A statistical evaluation of the mean values of dust retention efficiencies for both the spiked and unspiked samples shows no significant difference among the three types of collectors. The conclusions previously stated regarding the standard deviation of measured dustfall continue to hold for the calculated retention efficiencies.

The conclusions are based on experiments in which the exposure of containers included windy and rainy weather (Tables III and IV). The total precipitation in the 16 days of the first experiment was 2.03 in. compared to 3.17 in. for the 21 days in the second experiment. The first experiment also had lower daily average as well as lower daily five-minute maximum wind speeds, although winds as high as 26 mph. occurred. These weather data are fairly representative of fall and spring weather in a temperate climate. This study is being continued to include weather conditions representative of totally dry periods occurring in desert climate or in areas having dry summers.

Plastic containers have not been applied to dustfall collection to any appreciable extent, and it is possible that they have unsuspected superior dust retention because of their ability to become electrically charged. A study is being planned to investigate the effects of electro-static charge

TABLE III

Wind Speed Data

Cumulative Frequency Distribution of Daily Average Speeds

Mph.	Experiment 1 % Greater than	Experiment 2 % Greater than
4	76	92
6	43	63
8	21	33
10	10	15

Cumulative Frequency Distribution of Daily 5 Min. Max. Speeds

Mph.	Experiment 1 % Greater than	Experiment 2 % Greater than
8	80	89
10	56	74
12	36	58
14	20	42
16	8	30
18		20
20		13
22		9

build-up on the dust retention efficiency of polyethylene containers.

Conclusions

Dustfall collectors representing three collection techniques were exposed to atmospheric dustfall under weather conditions typical of a temperate climate. A statistical evaluation of the gravimetric analysis data and the dust retention efficiencies shows no significant differences among the three types of collections.

Acknowledgments

The author wishes to express his appreciation to Eugene Jochem and Carl Berry for their assistance in the experiments and to Dr. E. K. Harris for his assistance on the statistical aspects of the problem.

TABLE IV

Precipitation Data

Distribution of Periods of Consecutive Rainless Days

	Experiment 1	Experiment 2
Length of Period (Days)	Periods	Periods
1	3	2
2	0	2
3	1	0
4	2	0
5	0	2
6	1	0

Distribution of Periods of Consecutive Rainy Days

	Experiment 1		Experiment 2	
Length of Period (Days)	Periods	Avg. Ppt. (in./day)	Periods	Avg. Ppt. (in./day)
1	3	0.13	2	0.08
2	2	0.10	1	0.03
3	0	—	1	0.37
4	1	0.26	2	0.05
5	1	0.04	0	—
6	0	—	1	0.24

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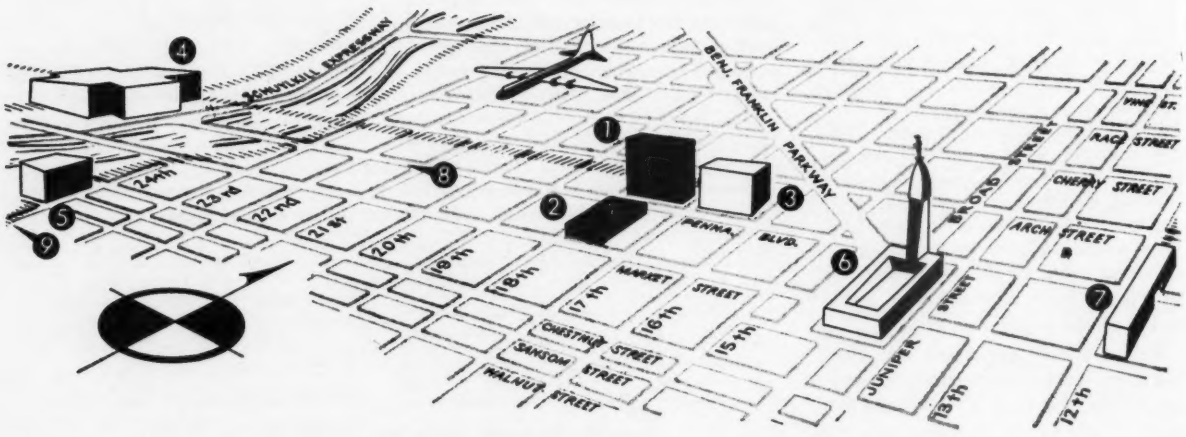

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2 Sheraton Garage
3 PRR Suburban Station
4 Pennsylvania Station 30th Street
5 Baltimore & Ohio Station
6 City Hall
7 Reading Station
8 To International Airport
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Engineering Design Factors in Dust and Fume Recovery Systems*

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This discussion is primarily in reference to dust and fume recovery systems where the gases are vented to the atmosphere and not reused.

No two plants in any industry are identical and have many variations and ramifications as to process equipment, operating characteristics, nature of raw material, emissions and air pollution control requirements. Problems also vary widely between different industries.

The engineering design of dust and fume recovery systems must consider the following major factors:

(1) Ordinances and statutory regulations.
(2) Plant and community requirements.
(3) Plant location: Topography, buildings, micrometeorology.
(4) Source control.
(5) New or existing equipment.
(6) Disposition of collected materials.
(7) Water disposal where scrubbers are used.
(8) Removal of dust and fume (particulate matter).
(9) Removal of noxious gases or odors.
(10) Removal or reduction of stack plume (opacity).

From the standpoint of the individual industrial plant, control is motivated by economic value of recovered material or value of cleaned gas, the legal requirements as covered by ordinances and statutory regulations and a desire on the part of the management to maintain satisfactory relations with the workmen as well as the neighbors in the surrounding communities.

Legal requirements vary over a wide range of permissible operating conditions covering particulate matter, noxious gases, opacity and odor[1]. They are affected by air pollution control ordinances, zoning ordinances, building codes, Department of Street and Sanitation regulations, city and state health codes.

To a large degree the extent to which the dust and fume system must remove air contaminants is governed by the community relations problems.

Purely from economics it may be shown in many cases that a collection efficiency of more than 80 to 90% cannot be justified. Nevertheless, it may be that for community requirements efficiencies of 99% or more are indicated.

A clean stack is only one part of the problem. The plant and its surroundings should also be kept clean. The accumulative effect of the two on public and labor relations cannot be overestimated.

The man with the broom and air hose is costly and is rapidly being replaced with industrial vacuum cleaning systems to clean the plant. This improves plant morale and makes for goodwill ambassadors in the community.

When the community understands that the plant management is making continuous effort to remedy or improve dust and fume conditions and the working conditions are relatively clean, both the employees and the community are inclined toward the company.

Conditions affecting local plant air pollution problems also include micrometeorology, terrain, adjacent buildings, use of adjacent property, number of contributing dust sources, total quantities involved and other air pollution sources in the area.

In the selection of a new plant location all of these should receive careful consideration. Future difficulties can be avoided by selecting a site that is well ventilated by winds, not subject to frequent low inversions or near-by built up commercial and residential areas.

With the population move to the country this is no longer an easy matter. Residential communities are being built by enterprising developers frequently adjacent to old, established industrial plants.

Existing plants must make the best of the situation and comply with existing regulations. However, where an ordinance is being considered, the plant management should take an active part in an effort to obtain regulations that are realistic and fit the local conditions.

Having established the overall requirements as dictated by regulations, plant location, community relations and related factors, all sources must be tabulated and studied individually. For many fuel burning operations in the power plant, steel and non-ferrous metallurgical industry much test data is available so that proper evaluation of the source is possible.

However, many times research studies are needed to determine the operating characteristics of the system.

This work involves:

(1) Review of available plant information and data.
(2) Tests and laboratory analyses to obtain dust and fume quantity and character.
(3) Pilot plant work if indicated.
(4) Calculations to establish the collection requirements.

Frequently there is no reliable data available and heat and material balances are the exception rather than the rule.

The study of new and old installations is not complete until it is decided what dust sources if any can be eliminated, what process modifications can be made to reduce dust loss and what raw material substitutions might be made to improve operation. In the latter category might be substitution of natural gas for oil or

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TABLE I

Affect of Air Infiltration Upon Electrical Precipitator Efficiency and Dust Loss From a Dry Process Cement Kiln

Assume air infiltration at 25% by vol. under good conditions.
Assume air infiltration at 100% by vol. under poor conditions.

	Good condition	Poor
Air infiltration — % by vol.	25	100
Precipitator gas vol. — Cfm.	100,000	134,500
Precipitator gas temperature — °F.	550	385
Gas moisture content — % by vol.	10	6.22
Inlet dust loading — gr./ft.^{3}	3	2.23
Design efficiency — %	98.5	
Dust loss — gr./ft.^{3}	0.045	
Dust loss — lb./hr.	38.6	
Dust loss — tons/day	0.408	
Calculated efficiency — % (based upon increase in gas vol. only)		95.5
Dust loss — gr./ft.^{3}		0.101
Dust loss — lb./hr.		116
Dust loss — tons/day		1.39
Calculated efficiency — % (based upon increase in gas vol. and reduction in moisture and temperature)		87.5 or less
Dust loss — gr./ft.^{3}		0.28 or more
Dust loss — lb./hr.		321.0 or more
Dust loss — tons/day		3.86 or more

coal as a fuel. This would eliminate the fly ash problem, reduce the SO_2, SO_3 and the stack plume.

For a dryer in a mixing plant it was found that field sand could be replaced with washed sand at little additional cost. Present cyclones were adequate and no new equipment was needed.

Review of the data sometimes indicates that modernization or modification of a process will reduce the dust loss, eliminating the necessity of adding new or improved collection equipment. In addition, changes may result in operating savings, such as improvement of thermal efficiency, reduction of operating labor, material handling and maintenance. It is obvious that the place to control air pollution is at the source, either by eliminating the source or reducing the contaminants emanating therefrom to a minimum.

Old installations usually offer special problems. Space is at a premium and field inspection frequently reveals that maintenance has been inadequate. The investment initially made in dust and fume control equipment has not been maintained.

Air infiltration is oftimes overloading the present collection equipment or interfering with its proper operation.

The affect of air infiltration on collectors such as a precipitator can be illustrated by using a dry process cement kiln as an example. Table I is based upon the hypothetical case of a gas-fired dry process cement kiln equipped with an electrical precipitator having a collection efficiency of 98.5% when first placed in service.

When newly put into service such an installation should not have an air infiltration in excess of about 25% by volume. After several years of service with inadequate maintenance the air infiltration increases. It is common to find that the kiln seal ring is not tight, cracks and openings have developed in the kiln end housing, flues, inspection openings and the like that provide sources of air leakage into the precipitator. Under such conditions infiltration is often 100%, or more.

In the case illustrated by Table I the gas volume has gone up 34.5%. From this cause alone it would be expected that the efficiency would go down from 98.5 to about 95.5% and the dust loss would increase from 0.408 tons/day (38.6 lb./hr.) to 1.39 tons/day (116 lb./hr.).

The gas temperature has gone down from 550 to 385° F. and the moisture content of the gas from 10 to 6.22% by volume. As a result of this the electrical resistivity of the dust would probably be in a very bad range from a precipitation standpoint[2]. Experience indicates that under these conditions the precipitator efficiency would drop to 87.5%, or less, with resultant dust loss of 3.86 tons/day (321.6 lb./hr.), or more.

Poor gas distribution is another factor that can greatly impair the efficiency of electrostatic and mechanical collectors. This can often be remedied or improved by proper use of turning vanes, splitters, perforated plates and baffles[3].

High dust loss has sometimes been found to be caused by recycling of dust within the system. This can be the result of such practices as returning collected dust to the system at a point where it is readily re-entrained.

In the cement industry this problem has been overcome to a great degree by special dust handling methods. In dry process plants the dust is usually returned to the raw feed bins where it is blended with the new feed. In wet process plants it is often pugged into the new feed slurry. A recent innovation is to reintroduce the dust as dust or nodules in scoops around the periphery of the kiln at a point some distance below the feed end so that in effect it is introduced under the new feed to the kiln.

In new plants the designer should keep in mind that the dust and fume control equipment is the last unit process in the system. In addition to providing modern recovery equipment, the designer should provide space for additional capacity that may be required later due to more stringent regulations or community requirements or increase in gas volume.

Plant operators invariably find ways and means of increasing the production of equipment. This usually contributes to an increased gas volume and dust concentration. It is not uncommon to see a given unit pushed up to 125 to 175% of rated capacity over a period of time.

Unless space has been provided for additional dust and fume recovery equipment, the air pollution problem may prevent the use of increased capacity.

New plant layouts should locate the stack keeping in mind the additional equipment that may be required. In some cases this may be equipment needed to remove the noxious gases not presently covered in the existing regulations.

Where plant capacity has been increased in existing installations involving changes in the process, it may be necessary to make changes in

TABLE II

Factors Affecting Collection Equipment Selection

(1.) Nature of material to be collected	
a. Dust only	from rock crushing
b. Fume only	zinc oxide production
c. Dust and fume	from cement kiln
d. Soluble solids	Na_2SO_4 and Na_2CO_3 from kraft paper mill black liquor recovery boiler
e. Noxious gases	SO_2 and SO_3 from coal or oil fired boiler
f. Tars or pitches	carbon plants
g. Acid mist	sulphuric acid manufacture
h. Corrosive	wet fluoride collection
i. Inflammable or explosive	magnesium dust collection
j. Not free flowing	furnace carbon black
(2.) Character of process operation	
a. Uniform continuous	electric utility boiler
b. Non-uniform continuous	open hearth steel furnace
c. Batch — single or multiple unit	gypsum kettles
d. Irregular intermittent	scarfing machine in steel plant
(3.) Technical data	
a. Gas volume	
b. Gas temperature	
c. Inlet loading to collector	
d. Particle size distribution of solids	
e. Specific gravity of solids	
f. Chemical composition of solids and gases	
g. Electrical resistivity of dust and/or fume	
h. Acid concentration or pH	
(4.) Other engineering considerations	
a. Wet or dry collection	
b. Single or multiple units in series or parallel	
c. Available space and equipment arrangement	
d. Flues including gas distribution, dampers, expansion joints and related facilities.	
e. Fans with controls and drives	
f. Dust handling and disposal systems and accessories	
g. Labor saving auxiliaries and features such as time cycle operation with filters, automatic voltage control and automatic rapping for electrical precipitators	
h. Instrumentation and controls	
i. Protective facilities, such as explosion diaphrams, traps, pressure relief devices and by-passes	
j. Permissible stack height and aircraft requirements	
k. Materials of construction	
l. Wind loads and seismic forces	

the collection equipment. In some cases satisfactory conditions may be maintained by re-cycling part of the gas to the process thus by-passing the collector or scalper collectors can be used to pre-clean the gas and thus remove some of the dust load from the existing equipment.

An existing scrubber may be modified and used as an excellent gas cooler for a new baghouse or as a conditioning chamber for a new precipitator. An existing precipitator may be improved and the overall collection efficiency materially raised by the use of a pre-cleaner, voltage control or automatic rapping.

The stack is an important part in any recovery system. It provides the ultimate dilution and dispersion to the atmosphere of the waste gas and remaining contaminants.

In addition it usually provides some draft for the operation of the system.

The layman's first and continuous appraisal of the plant's contribution to air pollution is the stack appearance. For this reason it is sometimes advisable to combine several sources in a single stack so as to overcome variations in the operations of the process and the associated recovery equipment and avoid direct comparisons between different stack effluents.

The selection of suitable stack height, size, outlet velocity and materials of constructions are influenced by such factors as local micrometeorology[4], proximity of local air fields, quantitative and qualitative nature of the emission and economics.

The atmosphere can dissipate enormous quantities of contaminants. In some cases it is more economical to resort to a high stack with a relatively high exit velocity rather than to attempt recovery of a major portion of the contaminants. This method is being used in some large central station power plants since there is no present economical method of removing SO_2 as it exists in waste boiler flue gas.

High stacks are one of the earliest methods used for waste gas disposal, particularly in the metallurgical industry.

Where high stacks are not feasible it is common to increase outlet gas velocity to 120 to 180 ft./sec. by the use of nozzles in the top of the stack. This assists in dilution and dispersion of the gases.

The local topography and configuration of surrounding structures has an important effect on stack height and outlet velocity.

In some cases it is desirable to make wind tunnel or field studies of these and other factors before establishing stack height and outlet velocity[5].

Temperature has an important effect on dilution, and to a large degree determines the materials of construction.

Concentration of gaseous and particulate matter, particle size distribution and terminal velocities must be considered.

Coarse material discharged from a stack may be scarcely visible but still represent a control problem. Generally such emissions fall on the plant property or close to the stack. Examples of this type of discharge are cement clinker coolers, iron ore sintering machines and spreader stoker fired boilers. In general, these problems are solved through the use of high efficiency, cyclonic type of mechanical collectors.

Finely divided particulate matter, such as material that volatizes in process and condenses as a fume, leads to problems in opacity or obscuring power of the stack effluent. In some cases material has agglomerating characteristics and a condition referred to as *snowflaking* may be experienced even though 99% or more of the particulate is removed. Large agglomerates fall in the immediate area and in the case of cement plants and black liquor recovery waste gases in paper mills, can create a great nuisance even though high efficiency recovery equipment is installed.

Final stack selection is usually dependent upon engineering and economic factors coupled with experience and engineering judgment.

Plants that can reuse their collected dust and fume by returning it to the process are very fortunate. Many plants are faced with disposal of their collected dust. This frequently poses difficult problems and

can be expensive.

The experiences of the electric utility companies with large coal burning generating stations illustrate the magnitude and nature of the problem[6].

For between 25 and 30 years efforts have been made to use fly ash from pulverized coal fired boilers as a concrete additive. Much investigation by various agencies has been conducted in this field over the years. Considerable fly ash has been used. However, the total quantity of fly ash collected in some eastern and middle-western metropolitan centers is so enormous that it must be pumped or hauled for landfill or loaded into ocean-going barges and hauled to sea.

American cement manufacturers are studying the possibility of using fly ash as a part of the raw mix for cement.

The dust disposal problem from plant to plant is extremely variable. Some cement plants pump it or haul it to abandoned quarries. When this is done, it must be wetted and packed or it will blow over the neighborhood. One cement company piled it near a lake at the plant site. Rain water leached the alkalis out of the dust and raised the alkalinity of the lake water. The State Fish and Game Commission made the company cease and desist from piling the dust at that location on their own property.

Most municipalities will not permit emptying industrial waste into sewers. Also they will not permit dust to be transported through city streets unless it has been completely wetted or is hauled in completely enclosed trucks.

Other factors to be considered in the design work are: *(1)* future plant expansion, *(2)* arranging space for additional equipment and *(3)* the affect of tighter future ordinances on the current installations.

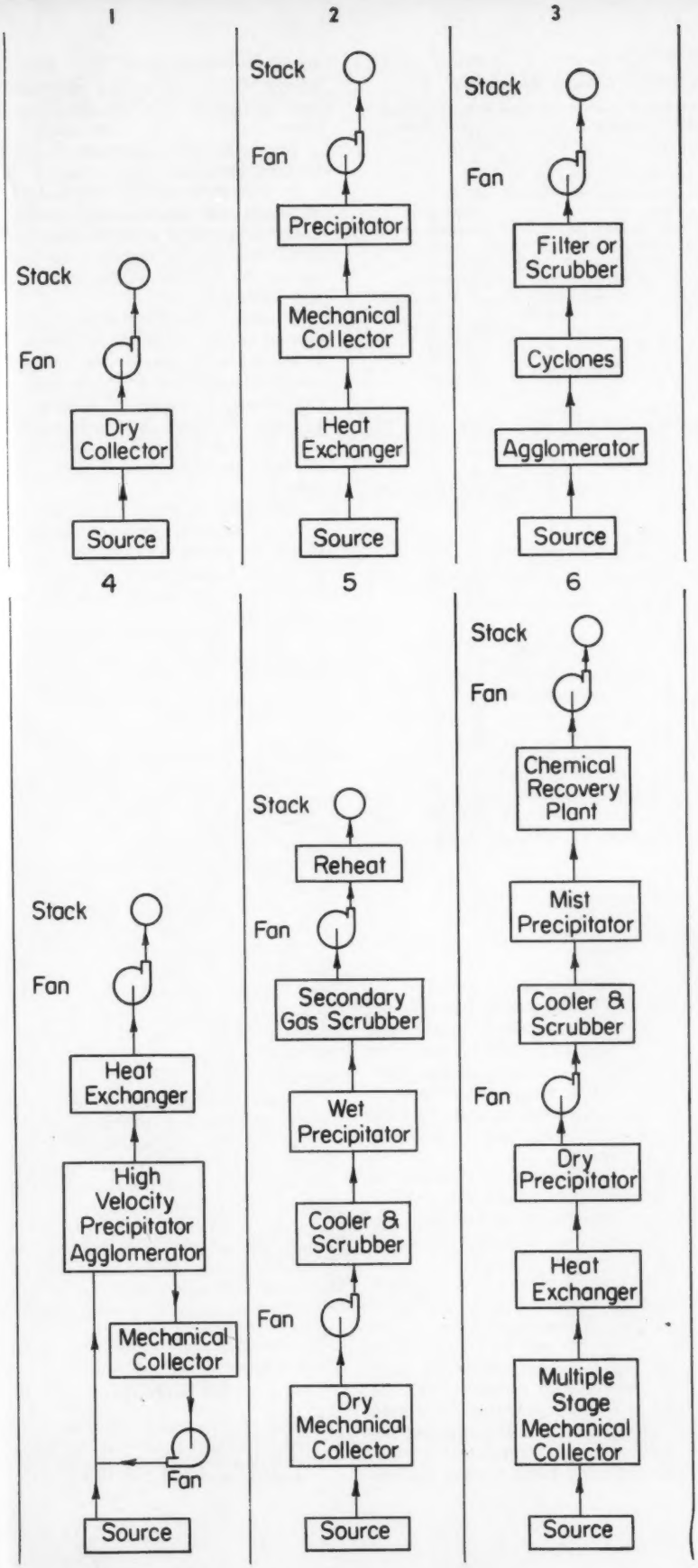
Economical and practical equipment selection to meet the requirements depends upon many factors and availability of a substantial amount of information and data. A partial list of the type of information needed and considerations involved

CHART I

Check List of Collector Applications

	Dry electrical precipitators	Wet electrical precipitators	Baghouses	Reverse-jet filters	High efficiency cyclones	Scrubbers	Conditioning and cooling chambers*	Low draft loss cyclones	Low draft loss mechanical
Aluminum									
Prebaked pot line	X	—	Xg	—	X	X	—	—	—
Old type Soderberg pot line	—	X	—	—	—	X	—	—	—
New type Soderberg pot line	—	—	—	—	X	X	—	—	—
Electrode plant ventilation	X	—	—	—	—	—	—	—	—
Bauxite dryer	X	—	—	—	X	—	—	—	—
Alumina calcining	X	—	—	—	X	—	—	—	—
Cement									
Kilns	X	—	Xg	—	X	—	—	—	—
Clinker coolers	—	—	—	—	—	—	—	X	X
Blending vents	—	—	X	X	—	—	—	—	—
Finish grinding	X	—	X	—	—	—	—	—	—
Rock and shale dryers	X	—	—	—	X	—	—	—	—
Chemical									
Acid manufacture	—	X	—	—	—	X	—	—	—
Phosphate dryers	—	—	—	—	X	X	—	—	—
Electric phorphorous furnaces	X	—	—	—	—	—	—	—	—
Carbon black — furnace plants	Xa	—	X	—	—	—	—	X	—
Iron and steel [1]									
Blast furnaces	—	X	—	—	—	X	—	—	X
Open hearth furnaces[3]	X	—	—	—	—	—	—	—	—
Sintering machines	X	—	—	—	X	—	—	—	X
Electric furnaces[9]	X	—	X	—	—	—	X	—	—
Scarfing machines	X	—	—	—	—	—	—	—	—
Oxygen crucibles	X	—	—	—	—	X	X	—	—
Foundry cupolas [10, 11]	X	—	X	—	—	X	—	—	—
Non-ferrous smelters [12]									
Roasters	X	—	—	—	X	—	—	—	—
Reverberatories	X	—	—	—	—	—	—	—	—
Converters	X	—	—	—	X	—	X	—	—
Sintering machines	X	—	—	—	—	—	X	—	—
Blast furnaces	—	—	X	—	—	—	X	—	—
Power generation boilers [13]									
Pulverized coal fired	X	—	—	—	X	—	—	—	—
Cyclone furnace	X	—	—	—	X	—	—	—	—
Spreader stoker	—	—	—	—	X	—	—	—	—
Oil fired	—	—	—	—	X	—	—	—	X
Pulp and paper									
Black liquor recovery boilers	X	—	—	—	—	X	—	—	—
Reclaimed lime kilns	X	—	—	—	—	X	—	—	—
Hogged fuel boilers	—	—	—	—	X	—	—	X	X

* Used for conditioning and/or cooling gases ahead of precipitator or baghouse.
g Glass cloth bags.
a Used as an agglomerator.



is given in Table II.

Chart I is a check list of collector applications for various operations in a few industries. It does not include all operations in each industry that require dust control. This chart can be used as a general guide in equipment selection and must be supplemented by more detailed technical, engineering and economic studies.

The types of equipment checked are typical for the application but there are exceptions in actual operation.

From time to time new technological developments change collector applications. Recently the development of silicone treated glass cloth has aroused interest by the cement industry for baghouses for cleaning cement kiln gas. Previously such an application was not considered seriously because of the temperature limitations of available fabrics.

It will be noted that the chart usually shows more than one piece of equipment for a given application.

A single piece of equipment may not give the desired result and oftimes several different types must be used in series. The possible arrangements are limited only by the designer's ingenuity.

Chart II shows some typical dust and fume process flow diagrams now in use, starting with the very simplest system having a source followed by a dry collector, fan and stack.

Column 2 indicates a source followed by a heat exchanger, mechanical collector, precipitator, fan and stack. This is common on pulverized fuel fired boilers.

Column 3 indicates a source such as a carbon black furnace followed by an electrostatic agglomerator, cyclones, filter or scrubber, fan and stack.

Column 4 shows a source such as an oil fired boiler followed by a high velocity continuous electrostatic precipitator from which the agglomerated material is removed in a small recycled portion of the total gas flow and collected in a mechanical collector. The agglomerator is followed by heat exchanger, fan and stack.

Column 5 indicates a series of equipment for a new cement plant. The installation will consist of a mechanical collector fan, cooler and scrubber, wet precipitator, fan, reheat chamber and stack. Space will be provided in the initial installation for a secondary gas scrubber. This system will remove a dry coarse fraction

TABLE III

Range of Inlet Loadings and Particle Sizes for Collector Applications

	Inlet Loading gr./ft.³	Particle Size % Minus 10 μ
Aluminum		
Prebaked pot line	0.2 to 0.5	25 to 35
Old Type Soderberg pot line	0.04 to 0.1	tar fog
New Type Soderberg pot line	0.2 to 0.5	tar fog
Electrode plant ventilation	0.1 to 1.0	
Bauxite Dryer	2 to 10	20 to 35
Alumina Calcining	5 to 40	10 to 30
Cement		
Kilns	1 to 15	40 to 50
Clinker Coolers	0.2 to 1	5 to 20
Finish Grinding	2 to 10	40 to 50
Rock and Shale Dryers	4 to 25	10 to 30
Chemical		
Acid Mist	0.03 to 0.06	
Phosphate Dryers	3 to 10	
Electric Phosphorous Furnaces	0.2 to 2	95 to 99
Iron and steel		
Blast Furnaces (after scrubbers)	0.1 to 0.5	95 to 99
Open Hearth Furnaces	0.2 to 4.0	97 to 99
Sintering Machines	2 to 5	10 to 50
Electric Furnaces	0 to 5	97 to 99
Scarfing Machines	0 to 0.1	fume
Oxygen Crucibles	0 to 5	97 to 99
Foundry Cupolas	0.3 to 1	70 to 85
Non-ferrous smelters		
Roasters	2 to 50	10 to 30
Reverberatories	2 to 5	50 to 60
Converters	0 to 10	10 to 50
Sintering Machines	0.3 to 5	10 to 50
Power generation boilers		
Pulverized coal fired	1 to 6	25 to 45
Cyclone Furnace	0.25 to 0.75	80 to 85
Spreader Stoker	5 to 15	10 to 15
Oil Fired	0.02 to 0.07	± 99
Pulp and paper		
Black Liquor Recovery	1 to 5	fume
Reclaimed Lime Kilns	2 to 5	25 to 40
Hogged Fueil Boilers	2 to 10	± 5

then cool, dehumidify and scrub the gas reducing the volume approximately one-half. The wet electrostatic precipitator will remove 99% of the remaining fume and the gases will then be reheated to eliminate the stack plume.

Column 6 shows a source such as a non-ferrous smelter followed by a multiple stage mechanical collector, heat exchanger, dry precipitator, fan, cooler and scrubber, mist precipitator, chemical recovery plant, fan and stack.

Chart III shows the approximate dust loading and particle size for a number of process operations. It should be kept in mind however that, as has been pointed out, these vary over a wide range and there may be exceptions that are far outside the limits indicated. This can be used as a general guide where more precise information is not available.

So far the discussion has referred to recovery equipment, stacks and dust disposal. In addition, each dust and fume system has several other essential parts, all of which must be carefully integrated in order that the process as a whole will be practical and economical.

Much information is available in the literature on hoods, flue calculations and design along with such devices as splitters, turning vanes and various types of connections.

Performance of any dust collector, however, is dependent to a degree, sometimes almost controlling, on the satisfactory gas and dust distribution at the inlet. Flues should be carefully checked and reviewed with the supplier of the collector to obtain his approval of the arrangement before the flues are fabricated[7].

All dust and fume control systems require a satisfactory fan. This is ordinarily placed beyond the collectors to handle as clean gas as possible.

The collector supplier can be asked to recommend a suitable fan.

It is best to use the simplest possible fan and avoid complicated fan blade designs and arrangements. Dust sometimes has a tendency to build up on the back of blades and cause fan unbalance.

Whenever the characteristics of the system cannot be precisely defined it is desirable to provide the fan with a variable speed or tex rope drive so that its speed can be adjusted to the system. Fans are ordinarily selected with the safety factor of 25 to 30% on both gas volume and static pressure.

The design engineering of dust and fume recovery systems for industrial plants to assure an economical and practical installation that meets requirements can be divided into several phases.

Control requirements include consideration of present and proposed ordinances and statutory regulations as they relate to the installation. It also envisions local community, public and labor relations insofar as plant cleanliness and stack appearance are concerned. It includes dust disposal, future plant expansion, stricter ordinances and space for future additional equipment.

Source control envisions study and research to find out what is happening in the process and evaluation of the problem. This includes changes in the process to eliminate or reduce the dust loss from the process. It also includes rehabilitation of existing process equipment, elimination of sources of air infiltration, recycling of dust and other adverse operation conditions.

Control equipment considers the whole engineering problem of collector selection and associated equipment and facilities to meet the overall dust and fume control requirements. Judicious consideration of alternative types of equipment or combinations and arrangements depends to a great extent upon past experience with and knowledge of failures and successes of similar installations.

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The Collection of Silica Fume with an Electrostatic Precipitator*

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Columbus, Ohio

This is the second paper of a series describing work done by the Fuels and Air Pollution Division of the Battelle Memorial Institute, under a joint program sponsored by the Keokuk Electro-Metals Company and the Tennessee Products and Chemical Corporation, on the collection of silicon fume from electric arc furnaces. Previous studies on silica-fume collection were concerned with a high draft loss scrubbing device and have been described earlier.(1)

In the production of ferrosilicon in an electric arc furnace, a number of side reactions occur which result in the formation of gaseous silicon monoxide (SiO).(2,3) The silicon monoxide gas upon contacting the relatively cool atmosphere air is oxidized to minute solid spherical particles of silica (SiO_2). These small spherical silica particles pour from the furnace as clouds of fume. The furnace gases also carry with them particles of coke, rock, and iron oxide whose size distribution is markedly greater than silica-fume particles. Relative to the silica fume the coke, rock, and iron oxide dust represent a small fraction of the total number of particles in the furnace exhaust gases. Thus, the air pollution problem associated with the production of ferrosilicon in electric arc furnaces is one primarily of plume opacity.

Fig. 1 shows an electron micrograph of silica fume collected over an electric arc furnace producing ferrosilicon. The silica-fume particles

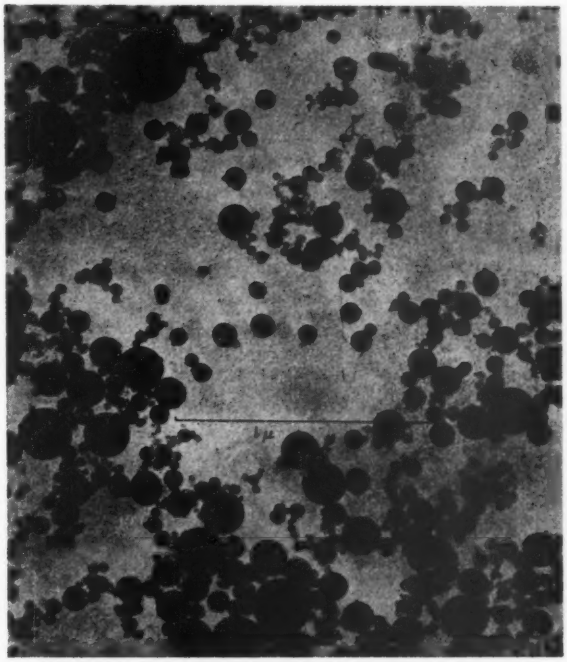

Fig. 1. Electron micrograph of silica fume particles.

*Presented at the Semi-Annual Technical Conference of the Air Pollution Control Association, Nov. 18-19, 1957, in the Fairmont Hotel, San Francisco, Calif.

AIR POLLUTION CONTROL

51st Annual Meeting

Sheraton Hotel, Philadelphia, Pa.

SUNDAY, MAY 25, 1958

Early Registration
Third Floor — Hotel Sheraton

MONDAY MORNING

SESSION 1-A

Community Surveys

Chairman: ARTHUR C. STERN, U. S. Public Health Service

The New York-New Jersey Interstate Air Pollution Survey. Louis C. McCabe, Resources Research, Inc.

The Houston Air Pollution Survey. Herbert C. McKee, Southwest Research Institute.

The Louisville, Kentucky, Air Pollution Study. August T. Rossano, Jr., U. S. Public Health Service, and Norman E. Schell, Kentucky State Department of Health.

An Aerometric Survey of the City of Honolulu. Philip J. Charley, Truesdail Laboratories, Inc., and Robert S. Nakamoto, Hawaii Department of Health.

Some Results of the Detroit-Windsor Air Pollution Study. Morris Katz, Department of National Health & Welfare, Ottawa, Canada, and J. J. Schueneman, U. S. Public Health Service.

An Air Pollution Study of Bridgeport, Connecticut, and Two Adjoining Communities. William G. Christy, Consulting Engineer, New York City.

General Session

SESSION 1-B

Chairman: C. A. BISHOP, United States Steel Corporation

Sampling and Analysis of Incinerator Flue Gases. Morris B. Jacobs, M. M. Braverman, S. Hochheiser, and I. Ettinger, Bureau of Laboratory, Department of Air Pollution Control, City of New York.

A High-Flow Millipore Tape Sampler. John S. Nader, U. S. Public Health Service.

Filters and Filter Media for Cement Plants. Richard F. O'Mara and Carl R. Flodin, O'Mara and Flodin, Inc., Los Angeles.

Simultaneous Removal of Acid Gases, Mists and Fumes with Mineral Wool Filters. Charles E. Billings, Charles Kurker, Jr. and Leslie Silverman, School of Public Health, Harvard University.

MONDAY AFTERNOON

SESSION 2-A

Incineration

Chairman: RICHARD C. COREY, U. S. Bureau of Mines

Incinerator Design Standards. William T. Ingram, College of Engineering, New York University.

Experimental Study of Incineration. A. A. Orning, J. J. Pfeiffer, W. C. Harrold, and J. F. Shultz, U. S. Bureau of Mines.

Air Pollution Effects of Firing Practices and Combustion Air Distribution on Incinerator Operation. Andrew H. Rose, Jr., R. L. Stenburg, M. Corn, R. R. Horsley and D. R. Allen, U. S. Public Health Service.

Performance of a Flue-Fed Incinerator. E. R. Kaiser and J. Halitsky, New York University; M. B. Jacobs, Bureau of Laboratory, Department of Air Pollution Control, City of New York; and L. C. McCabe, Resources Research, Inc.

Thermal Destruction of Low Concentrations of Acetaldehyde Vapor and Carbon Monoxide. John H. Ludwig, U. S. Department of Health, Education, and Welfare.

SESSION 2-B

General Session

Chairman: WALKER PENFIELD, Pennsalt Chemicals Corp.

Experiences in Controlling Atmospheric Pollution Encountered in Pharmaceutical Manufacturing Processes. William C. Johnson, The Upjohn Company, and Lloyd L. Kempe, University of Michigan.

A Review of the Air Pollution Research Program of the Smoke and Fumes Committee of the American Petroleum Institute. Charles A. Jones, API Smoke and Fumes Committee.

System Designs for Catalytic Decomposition of Nitrogen Oxides. J. L. Donahue, Catalytic Combustion Corporation.

Detection of NO_2 in Air with Dry Detector Papers. Charles Gelman, School of Public Health, University of Michigan; Robert Gamson and Harold Klapper, Chemical Warfare Laboratories, Army Chemical Center, Maryland.

TUESDAY MORNING

SESSION 3-A

Status of the Automobile Exhaust Problem

Chairman: C. M. HEINEN, Chrysler Corporation

The Chemical Nature of the Particulate in Irradiated Automobile Exhaust. N. A. Renzetti, Air Pollution Foundation, and G. J. Doyle, Stanford Research Institute.

Fuel Composition in Relation to Smog-Forming Exhausts. Leslie A. Chambers, Los Angeles County Air Pollution Control District.

Oxy-Dieseler Exhaust Purifier. M. R. Ericksson, Oxy-Catalyst, Inc.

The Infrared Analysis of Trace Gases Using Long Path Gas Cells and Ordinate Expansion. Raymond R. Sawyer, and Norman I. Adams, III, The Perkin-Elmer Corporation.

SESSION 3-B

General Session

Chairman: HAMNETT P. MUNGER, Syracuse University

Effects of the Steel Strike on Air Pollution Levels in Several Communities. Elbert C. Tabor and James E. Meeker, U. S. Public Health Service.

Weather Bureau Research on Air Pollution Potential. Lester Machta, J. Korshover, and G. Scott, U. S. Weather Bureau.

Meteorological Engineering and Community Air Pollution Surveys. Sidney R. Frank and Raymond E. Kerr, Jr., North American Weather Consultants.

Helicopter Utilization in Air Pollution Studies. R. H. McQuain and R. C. Wanta, U. S. Weather Bureau.

TUESDAY AFTERNOON

SESSION 4-A

General Session

Chairman: LEO P. FLOOD, Department of Air Pollution Control, New York City

Field Use of an Improved Smoke Inspection Guide. Andrew H. Rose, Jr., and John S. Nader, Public Health Service, Cincinnati, Ohio.

Testing of Domestic Incinerators. Morton Sterling and R. Bower, Air Pollution Control Bureau, Detroit, Michigan.

Investigation of a Design for an Automobile Body Burning Incinerator. Richard B. Engdahl, Battelle Memorial Institute, Columbus, Ohio.

Legal Problems Arising from the Banning of Open Burning in Philadelphia. Thomas Masterson, Law Department, Philadelphia.

CONTROL ASSOCIATION

Annual Meeting

Philadelphia, May 25-29, 1958

SESSION 4-B

Evaluation of Wind Tunnel Studies

Chairman: HARRY MOSES, Argonne National Laboratory

Use of Wind Tunnels in Study of Atmospheric Phenomena. J. E. Cermak and M. L. Albertson, Colorado State University Research Foundation.

Air Pollution Applications of Wind Tunnel Experiments. Gordon H. Strom, College of Engineering, New York University.

Wind Tunnel Studies — Past and Future. R. H. Sherlock, University of Michigan.

The Use of a Wind Tunnel in the Evaluation of Gummed Film for Radioactive Fallout Measurements. Jan Rosinski, and Samuel Radner, Armour Research Foundation.

WEDNESDAY, MAY 28, 1958

WEDNESDAY MORNING

SESSION 5-A

Public Relations

Chairman: ROBERT L. CHASS, Los Angeles County Air Pollution Control District

Public Information: An Important Tool in the Los Angeles Smog Fight. Arthur A. Atkisson, George DeKoven, and Robert M. Barsky, Los Angeles County Air Pollution Control District.

Air Pollution Control Is Good Business. William R. Bradley, American Cyanamid Company.

A Case History of the Utah Fluorine Problem of United States Steel Corporation. Arthur R. McQuiddy, U. S. Steel Corporation.

A Realistic Look at Fume Control. Harry L. Richardson, Research-Cottrell, Inc.

SESSION 5-B

Use of Environmental Chambers to Study Air Pollution Problems

Chairman: LEWIS H. ROGERS, Air Pollution Foundation

Facilities and Techniques for Maintaining Controlled Fluoride Environment in Vegetation Studies. A. C. Hill, L. G. Transtrum, M. R. Pack, and A. Holloman, Jr., United States Steel Corporation.

Design Considerations and Performance of Animal Exposure Chambers for Low-Level, Long-Term Studies. David A. Fraser and Herbert E. Stokinger, U. S. Public Health Service.

Large Chambers for Smog Research. F. V. Morriss, Midwest Research Institute.

An Air Pollution Test Chamber. R. D. Englert, Stanford Research Institute.

Design and Characteristics of a Controlled Environment System for Air Pollution Studies. K. W. Wilson and H. Buchberg, University of California at Los Angeles.

WEDNESDAY AFTERNOON

Industrial tours and visits to historical places in and around Philadelphia.

WEDNESDAY EVENING CONFERENCE

6:30—Cocktails.
7:00—Dinner ($5.00).
Joint Dinner meeting with Franklin Institute.
Subject: "Can Smog Come To Your City?"

7:30-11:00 P.M.
Control Officials Informal Discussion Session — Chairman: ROBERT L. CHASS, Los Angeles County Air Pollution Control District

THURSDAY MORNING

SESSION 6-A

Administration Problems of an Air Pollution Control Office

Chairman: H. K. KUGEL, Department of Licenses and Inspections, Washington, D. C.

Panel Discussion On:

Measurement of Progress in Air Pollution Control. J. H. Carter, Division of Smoke Regulation, St. Louis, Mo.

Training of Inspectors. Smith Griswold, W. H. Parmelee and L. H. McEwen, Air Pollution Control District, Los Angeles, California.

Coding and Recording Air Pollution Violations. Charles W. Gruber, Bureau of Air Pollution Control and Heating Inspection, Cincinnati, Ohio.

Community Participation in the Drafting of Regulations. Raymond Smith, Department of Public Health, Air Pollution Control Section, Philadelphia, Pa.

Cooperation in the Administering of an Air Pollution Control Program. Raymond E. Wetzel, Bureau of Air Pollution Control, Indianapolis, Ind.

SESSION 6-B

Health Effects of Air Pollution

Chairman: WILTON M. FISHER, U. S. Public Health Service

Air Pollutants As Respiratory Irritants — Observed Changes in Function and Metabolism of Lung Tissue. Lester D. Scheel, O. J. Dobrogorski, J. T. Mountain, J. L. Svirbely, and H. E. Stokinger.

Crop Dusting As An Air Pollution Problem. Wayland J. Hayes, United States Public Health Service.

Biochemical Effects of Air Pollutants: II—Experimental Evaluation by In Vitro Techniques. J. H. Gast and F. L. Estes, Baylor University College of Medicine.

An Index of Air Pollution and Its Relation to Health. N. E. Manos.

Some Considerations in the Interpretation of Air Pollution Health Effects Data. R. E. Prindle.

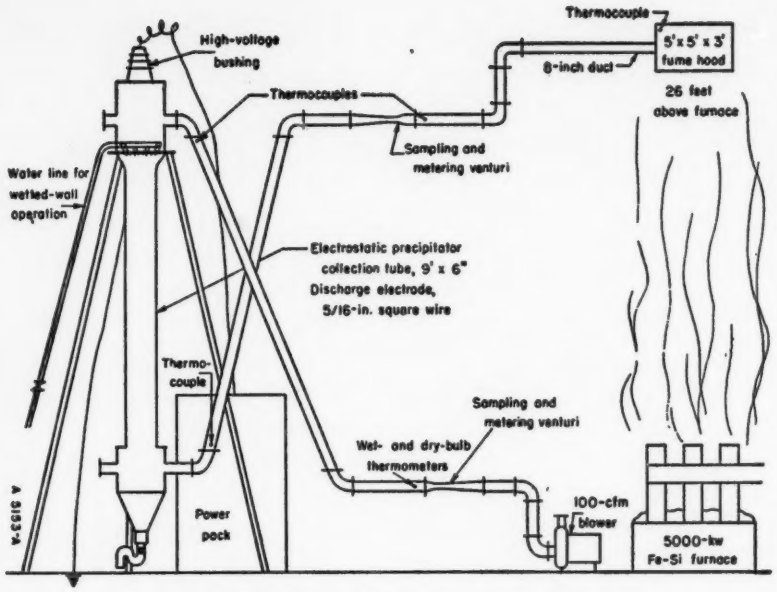

Fig. 2. Schematic diagram of electrostatic precipitator installation.

are spheres whose diameters were generally within the range between 0.01 and 0.5 μ.

Chemically, silica-fume analyzes between 50 and almost 100% SiO_2. Smaller quantities of iron, manganese, aluminum, magnesium and carbon are also present. The color of the collected fume is from grey to off-white. Silica fume has a low bulk density on the order of 11 to 12 lb./ft.[3]

This paper reports the results obtained with a pilot-scale electro-static precipitator. The objectives of this study were to determine the weight efficiency of fume collection and to make an estimate of the economics of electrostatic precipitation as applied to silica-fume collection.

Equipment and Procedure

Fig. 2 is a sketch of the electrostatic precipitator installation used.

The pilot electrostatic precipitator consisted of a single vertical collection electrode in the form of a tube of 6 in. ID, 9 ft. long. Suspended in the center of the collection electrode was a single discharge wire 5/32 in. square energized from an 8 KVA.-vacuum-tube power pack. The unit was equipped with spray nozzles to allow wetted-wall operation.

Briefly described, the operation of the electrostatic precipitator involved energization of the discharge wire with a negative high voltage sufficient for corona discharge. The furnace gas molecules near the vicinity of the discharge wire were dissociated into positive and negative ions under the action of the corona discharge. The negative ions, in being repelled from the negatively charged discharge wire, contacted fume particles and imparted charges to them. These negatively charged fume particles migrated to the grounded collection electrode and deposited there. The collected particles were either dislodged from the collection electrode by rapping the outer walls of the electrode or washed off by the descending water stream during wetted-wall operation.

The inlet of the electrostatic precipitator was connected by 8-in.-diam. sheet steel ducting to a 5 ft. x 5 ft. x 3 ft. hood suspended directly over the center and 26 ft. above a 5000 KW. furnace producing 50% ferrosilicon. (Under normal operation, furnace fumes and gases simply rose to the top of the building and passed out through a monitor.) Two specially constructed sampling and metering venturis were installed in the inlet and outlet lines of the electrostatic precipitator. A dampered 100-cfm. blower, located in the exhaust line, drew furnace gases through the electrostatic precipitator.

Fig. 3 is a sketch of the sampling and metering venturi used. Essentially the venturi was of standard meter design with the addition of two sampling ports welded to the divergent section of the meter. One of these sampling ports held a sampling probe positioned directly in the center of the furnace gases issuing from the throat of the meter. Samples were obtained in these venturis to eliminate any errors due to nonhomogeneous fume concentrations which might exist in the 8-in. duct, and to provide sufficiently high gas velocities to permit the use of null-point sampling methods.

Fig. 4 is a sketch of a null-point sampling device used to obtain fume-loading samples.[4] Fume samples were collected on filter pads consisting of approximately 1.4-μ-diam. glass fibers (Owens-Corning Fiberglas PF 105). Calibrated rotameters connected to vacuum pumps monitored the sample flow rate.

A null-point sampling device was used to insure isokinetic sampling throughout each run. In principle, the null-point sampling probe balances the static pressure in the probe against the static pressure in the sampling and metering venturi. By connecting the lead from the probe static pressure tap and the lead mon-

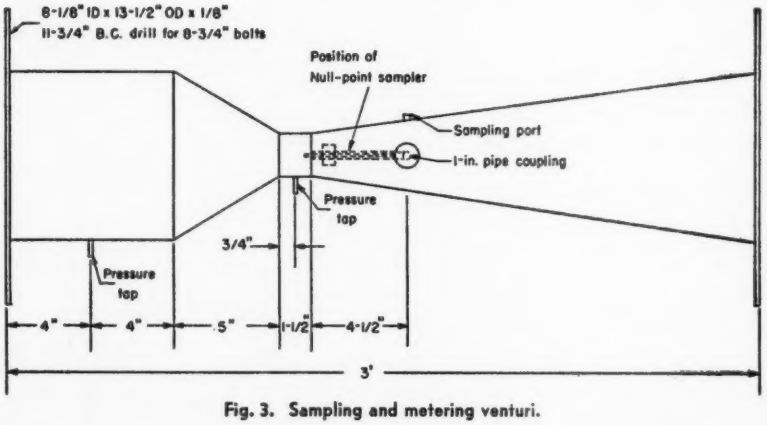

Fig. 3. Sampling and metering venturi.

itoring the venturi static pressure to opposite ends of a sensitive manometer, the state of balance of the system could be noted and necessary adjustments made quickly. The null-point sampling devices proved most useful since an appreciable quantity of fume deposited on the filter pads. This resulted in reduced flow, necessitating adjustments in gas sampling rates to maintain isokinetic sampling conditions.

Temperature measurements were obtained in the fume inlet hood, at the inlet and outlet of the electrostatic precipitator and finally at the sampling and metering venturis. A gas humidity measurement was taken in the exhaust lines of the electrostatic precipitator. The voltage in the primary windings of the transformer contained in the power pack and the amperage in the transformer secondary were also measured. Finally, the water-flow rate was recorded during wetted-wall operation.

The procedure for operation of the precipitator involved an equilibration period at a selected furnace gas flow rate followed by energization of the discharge wire. Fume samples were drawn through the null-point samplers, placed in the metering and sampling venturis prior to wire energization, and static pressures balanced on the manometers. Temperature, humidity, voltage, amperage, and fume-sampler flow rates were recorded during these runs which lasted between 15 and 80 min. Collection efficiency data were obtained from the weights of the filter pads before and after each run using an analytical balance.

Experimental Data

The experimental program involved the determination of collection efficiencies of untreated furnace silica fume during operation of the precipitator with *(1)* a dry collection electrode and *(2)* a continuously wetted collection electrode. In addition, a pair of preliminary runs were made with steam-conditioned silica fume while operating the collection electrode dry.

Dry-Collection Electrode Operation

Table I lists the results obtained with the pilot electrostatic precipitator during dry-collection electrode operation. Six runs were made while operating the electrostatic precipitator with dry silica-fume-containing furnace gases and an additional two runs were made with furnace gases treated with steam. All runs used half-wave rectified voltage for energization of the discharge wire. Half-wave-voltage operation was necessitated by the failure of one of the two rectification tubes in the power pack.

During these tests, inlet fume loadings varied between 26.45 and 57.06 mg./ft.^{3} at 60° F. and one atmosphere, depending upon variations in furnace operation. Furnace gas temperatures were also dependent upon furnace operation such that the gas temperatures in the precipitator were between 110 and 161° F. The gas

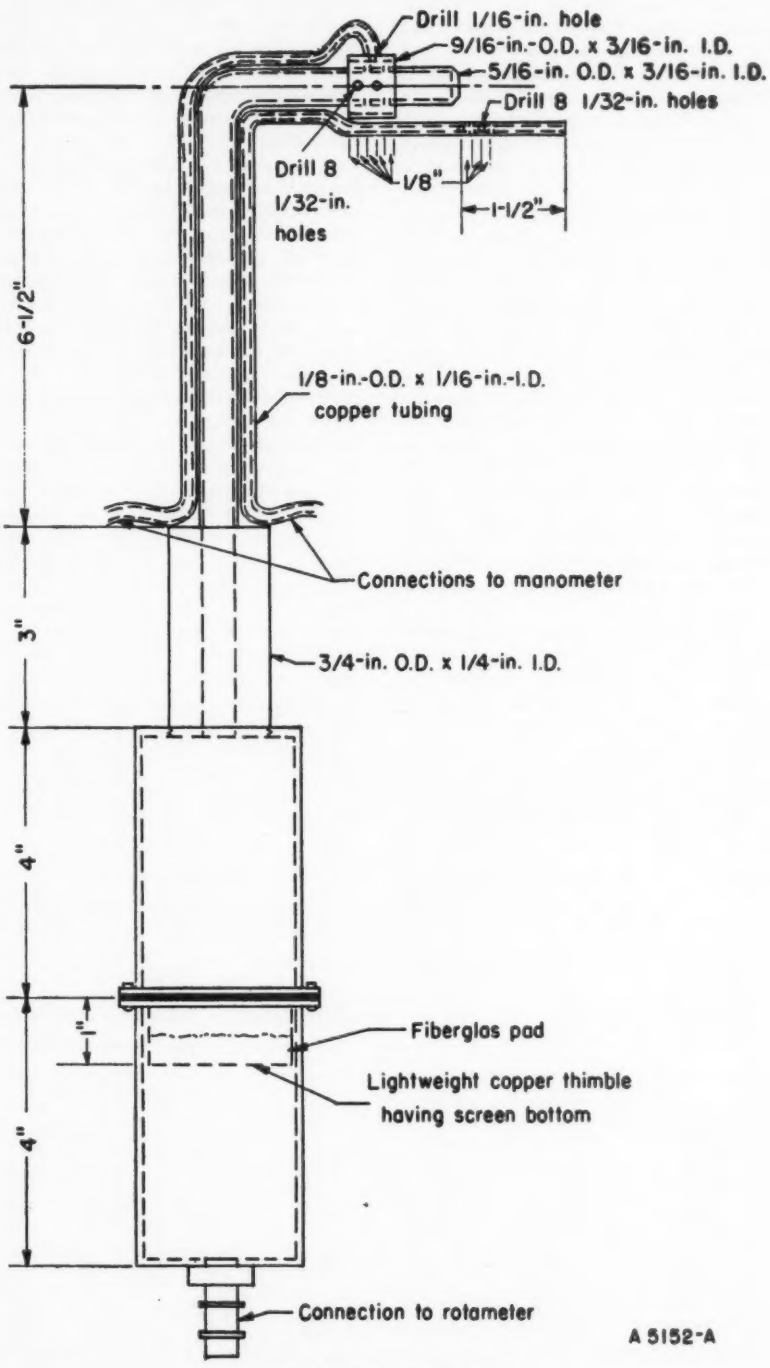

Fig. 4. Null point sampler.

velocity in the precipitator was varied from 3.07 to 6.15 fps.

The electrical operation of the precipitator was poor during these runs. As precipitated fume deposited upon the collection electrode it became impossible to maintain electrical operations at maximum power input due to excessive sparking. In general, power inputs had to be reduced 20 to 30% during the course of a run in order to operate the precipitator. Rapping of the collection electrode apparently had little effect indicating the rather tenacious hold of the silica fume upon the collection electrode.

The poor electrical operation found was characteristic of high resistivity dust precipitations.[5] Here the collected dust layer acts as an electrical insulator. Electric charges accumulate on the surface resulting in large voltage differentials between the upper and lower surfaces of the dust layer. The gases contained in the interstices of the dust layer tend to break down and emit ions thereby partially neutralizing the effects of the ions emitted from the discharge electrode. This condition of gas breakdown in the dust layer, commonly known as *reverse ionization*, results in reduced collection efficiencies and extremely rough electrical operation.

Although silica fume is apparently a high-resistivity dust, collection efficiencies in excess of 97% were obtained while operating the precipitator on dry untreated fume. These efficiencies, shown in Table I, may be somewhat misleading in that they probably represent time-dependent average collection efficiencies. Electrical operation became rougher during the course of a run and it would have been impossible to maintain corona discharge for much more than the 75 min. maximum running time tried. For commercial design it would be necessary either to provide an adequate rapping system for dislodging the collected fume or to periodically wash the fume off the electrode. The latter course of action appears to be wiser because of the difficulty experienced in removing silica fume by rapping of the collection electrode.

A number of methods have been devised for reducing the resistivity of industrial dusts. They involve increasing the conductivity of the dust layer by introducing small quantities of suitable conditioning agents. Moisture, sulfur trioxide and ammonia have been tried and shown to improve the precipitability of a number of high resistivity dusts.[6,7] Two runs were made in which steam was added to the silica-fume-containing furnace gases before they entered the precipitation zone. In the first run, gas relative humidity was raised to 74% while in the second the humidity was raised to 83%. Although these runs were insufficient to establish the effects of moisture on silica-fume collection, the electrical operation improved markedly. Contrary to the 20 to 30% reduction in power input required in order to operate the precipitator with dry fume, moisture-conditioned fume allowed electrical operation at a relatively constant power input. While the collection efficiency found with conditioned fume was no higher than an equivalent dry fume run, it is unlikely that the precipitator could have been operated at the same power input for as long a period dry as with moisture conditioned fume. Finally the precipitated moist fume was easily removed from the collection electrode by rapping.

To facilitate the use of the data obtained, average particle migration velocities were calculated and tabulated in Table I. The particle migration velocity is defined by the following relationship:[8]

$$w = -\frac{DV}{4L} \ln (1\text{-}E) \qquad (1)$$

where D is the inside diameter of the collection electrode, V is the gas velocity, L is the length of the collection electrode, and E is the precipitator collection efficiency. The particle migration velocity is related to the often used precipitator constant by

$$w = -\frac{D}{4} \ln (K) \qquad (2)$$

where k is the precipitator constant. The general practice has been to use Equation 1 in conjunction with experimental data obtained with pilot scale units to determine the particle migration velocity or precipitator constant. The particle migration velocity or precipitator constant is assumed to be constant for a given precipitator application such that commercial size electrostatic precipitators can be designed using data obtained with smaller units. Theory indicates, however, that the particle migration velocity is a function of dust particle size, precipitator charging

TABLE I

Summary of Electrostatic Precipitator Tests — Dry-Collection Electrode Operation, Half-Wave Rectification

Inlet Fume Loading, (1) mg./ft.³	Gas Velocity, ft./sec.	Gas Temp., ° F.	Gas Relative Humidity, %	Precipitator Input Voltage, KV. (RMS) Average	Maximum	Minimum	Collection Efficiency, %	Average Particle Migration Velocity, ft./sec.	Length of Run, Min.
				Dry Fume Operation					
52.59	6.15	153	30	27.3	——	——	99.05	0.43	14
26.45	3.07	117	43	37.0	42.0	32.7	99.40	0.24	75
32.47	3.54	129	38	30.7	42.0	25.5	99.91	0.37	60
34.79	4.82	148	32	32.7	43.2	25.0	97.36	0.26	60
32.43	5.75	161	25	33.4	43.2	26.1	98.89	0.39	45
57.06	4.08	110	57	28.4	36.8	25.2	99.61	0.34	60
				Steam Addition					
——	4.52	111	74	34.3	37.5	30.9	——	——	41
44.51	4.82	130	83	33.6	34.3	33.0	96.67	0.25	75

(1) Based on air at 60° F. and 14.7 psia.

and collection fields and gas viscosity. This theoretical relationship, however, has only been shown to be roughly in agreement with experimental data.[9] At any rate, it does not appear wise to scale up using an experimental value of the particle migration velocity or precipitator constant far removed from the conditions under which this particle migration velocity was obtained during pilot-scale runs. Finally, Equation 1 assumes a steady electrical field while actual electrostatic precipitators are operated with pulsating voltage forms. Therefore, the particle migration velocities calculated in this study are time dependent average velocities which were designated as average particle migration velocities.

The mean average particle migration velocity obtained during the precipitation of dry untreated silica fume was 0.34 ft./sec. A maximum deviation of approximately 30% was found between individual values of the average particle migration velocity, and the mean, and in part due to variations in gas temperature, precipitator operating voltage and possibly to length of sampling run which varied during this study. The average particle migration velocity found for silica fume during this study is in substantial agreement with a value of 0.41 ft./sec. calculated from data presented for a 42,000 cfm. commercial unit operating on dry silica fume from a 6000 kw. silicon-producing electric arc furnace.[10]

Wet-Collection Electrode Operation

An alternate approach to the efficient collection of a high resistivity dust involves the removal of the precipitated dust layer before sufficient electrical charge can accumulate and thereby disrupt the electrical operation of the precipitator. Dust removal is easily accomplished by directing a film of water over the collection electrode surfaces.

Table II lists the results of seven runs made with the electrostatic precipitator operating with a film of water running over the collection electrode surfaces. A water-flow rate of 1.8 *l.*/min. was maintained throughout. All wet-collection electrode runs used full-wave rectified voltage for energization of the discharge wire as opposed to the half-wave voltage form used during dry-collection studies.

During this study of wet-collection electrode operation, inlet fume loading varied between 12.27 and 55.33 mg./ft.^{3} (at 60° F. and one atmosphere). Gas temperautres in the precipitator were between 95 and 176° F. depending upon furnace operation. The gas velocity in the precipitator was varied from 1.87 to 6.07 ft./sec. In general, inlet fume loadings, gas temperatures and velocities during wet-collection electrode and dry-collection electrode studies were equivalent.

The electrical operation of the precipitator during wet-collection electrode runs was stable. The maximum voltage which could be maintained, however, was approximately 30% below the maximum voltages found during dry-collection electrode runs and indicated a significant effect of the water film upon the electrical operation of the experimental precipitator.

Collection efficiencies in excess of 92% were found during these runs. Calculated average particle migration velocities gave a mean average particle migration velocity of 0.25 ft./sec., as compared to 0.34 ft./sec. found during dry-collection electrode studies, possibly indicating the effects of voltage and voltage form upon precipitator efficiency. Though average particle migration velocities and efficiencies for dry-collection electrode runs appear to be greater than those found during wet-collection electrode runs, insufficient data were obtained to establish definitely these differences if they actually exist. At any rate, the results of this experimental study indicate the feasibility of collecting silica fume at high efficiencies in either a dry-or wet-collection electrode precipitator installation.

TABLE III

Cost of Operating An Electrostatic Precipitator on Ferrosilicon Furnace Gases

Basis: 88,000 cfm. of furnace gases	
Basis: 8,000 hr./operating year	
Capital investment, dollars	231,000
Capital investment, dollars/cfm.	2.63
Yearly Operating Expenses, dollars/cfm.	
Fixed Charges, 10%/year	0.263
Electricity at 1.0 cents/KW.HR.	0.047
Labor at $1.75/hr.[a]	0.054
Total Operating Costs	0.364

(a) Nine Man Hrs. per day

Costs of a Commercial Electrostatic Precipitator

An estimate of the capital investment costs and the operating expenses for a silica-fume electrostatic precipitator were made. A summary is given in Table III. An electrostatic precipitator of 88,000 cfm. capacity and an operating year of 8000 hrs. were assumed in making this cost estimate.

The capital investment was estimated to be 2.63 dollars/cfm. This is a high capital investment relative to a high-energy scrubbing device. Operating expenses on the other hand are lower than those necessary for operating a suitable scrubber. These cost estimates indicate that it would cost over $200,000 for a unit to

TABLE II

Summary of Electrostatic Precipitator Tests — Wet-Collection Electrode Operation

Inlet Fume loading,[1] mg./ft.^{3}	Gas Velocity, ft./sec.	Gas Temp., ° F.	Gas Relative Humidity, %	Precipitation Input Voltage, KV. (RMS) Average	Maximum	Minimum	Collection Efficiency, %	Average Particle Migration Velocity, ft./sec.
33.85	2.77	119	52	26.1	26.1	26.1	96.69	0.14
55.33	1.87	95	—	25.5	26.1	25.0	99.60	0.15
51.17	3.29	118	33	26.1	27.3	25.0	99.28	0.24
15.77	3.32	132	—	28.4	29.5	27.3	98.67	0.22
12.27	5.53	174	22	25.5	25.5	25.0	99.67	0.47
26.35	6.07	176	22	25.2	25.9	25.0	92.90	0.24
26.42	5.28	160	26	25.7	26.4	25.0	96.18	0.26

(1) Based on air at 60°F. and 14.7 psia.

handle all of the gases from a single 5000 kw. electric furnace. These costs would be extremely high for the small ferrosilicon manufacturer and indicates the need for drastic reduction of the volume of furnace gases by suitable hooding and enclosure.

Conclusions

The collection of silica fume at better than 90% efficiencies has been found to be feasible in either a dry or wet-collection electrode-type electrostatic precipitator.

Preliminary results with steam-conditioned fume indicated a marked improvement in precipitator electrical operation over that encountered with dry fume.

A cost estimate for a commercial size silica-fume precipitator indicates an investment cost of 2.63 dollars/cfm. of furnace gases treated.

Acknowledgment

Acknowledgment is made to Earl V. Harlow and Edward A. Wolfe at the Koppers Company for their assistance in planning and obtaining the data upon which this paper was based. Appreciation is also expressed to V. L. Kelley and the many other personnel of the Tennessee Products and Chemical Corporation for their gracious assistance during the experimental phase of this study and to R. B. Engdahl, Battelle Memorial Institute, under whose direction this work was done.

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Further Investigations of the Continuous Slag Wool Filter*†

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In the manufacture of steel by the open hearth process, a shallow bath of molten metal is reduced in carbon content by directing an oil or gas flame across the exposed upper surface. A roof above the bath directs the heat down onto the metal. Vaporization and agitation of the molten bath cause fine particles of iron oxide to be dispersed in the gas, along with the particles of other materials present in the reaction, such as lime, ore, and silicates. Mean size of these particles is less than 0.1 μ by count so that many are carried through the heat exchanger and on out the stack. Gas temperatures are about 1400°F. after leaving the heat exchanger. An average particulate loading of 0.4 gr./ft.^{3} may be present and for a 250 ton furnace this represents about a ton of fume/day.

† This report is based on work performed under a contract between Harvard University and the American Iron and Steel Institute.

* Presented at the 50th Annual Meeting of the Air Pollution Control Association held at St. Louis, Mo., June 2-6, 1957.

The American Iron and Steel Institute through its Subcommittee on Air Pollution Abatement is sponsoring research on high temperature gas cleaning at Harvard University. One phase of this research has been directed toward the use of slag wool as a filter fiber. Wool is made by spinning or blowing molten slag from the blast furnace, and its present primary use is for thermal insulation.

Investigations have proceeded from an analysis of the problem[1] through laboratory studies of the feasibility of using slag wool as an inexpensive refractory filter media[2], to the development and testing of a continuous pilot plant filter[3].

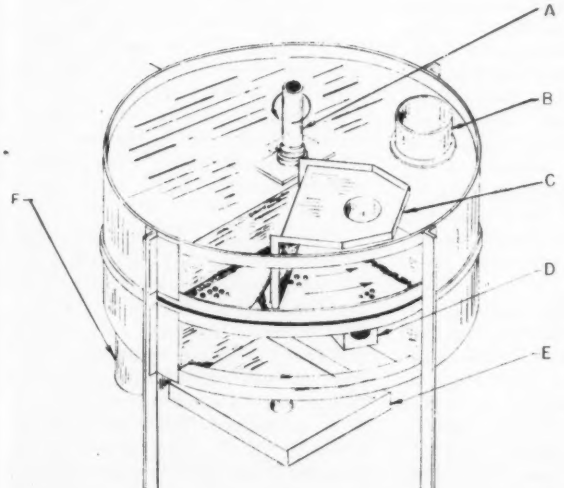
Fundamental requirements which have been set up for a slag wool filter for open hearth fume include removal efficiency of 95% of submicron fume from gases above 1000°F. while maintaining no more than 4 in. of water resistance to gas flow.

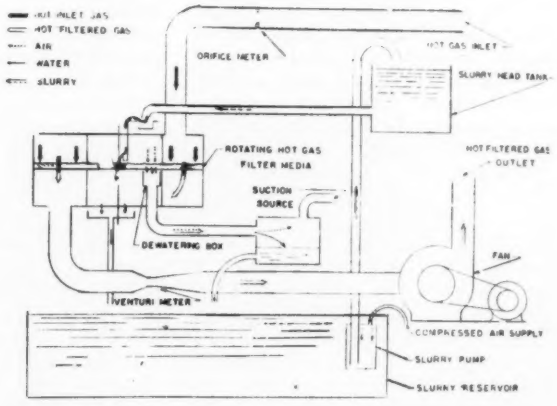
Laboratory studies have shown that a 1 in. thick layer of slag wool (at a packing density of 5 lb./ft.^{3}) will remove over 90% of a fine iron oxide fume from a 1000°F. gas stream at 100 fpm. filtering velocity. Resistance to flow is about 2 in. of water initially and increases as fume is collected. Each pound of fiber collects about 5% of its weight causing the resistance to rise an additional 2 in.

In the first pilot tests on an open hearth furnace[3], a continuous web of slag wool was formed from the fiber and was carried by a chain-belt conveyor into a gas plenum to filter the fume. An average collection efficiency of about 60% was obtained in this unit. Lowered efficiency was attributed to mechanical factors such as the difficulty of sealing the moving bed of fibers to a stationary surface and to thin areas in the bed produced during formation.

Additional slurry transfer and fiber washing equipment was also needed to evaluate the practicability of automatic continuous filter operation.

With the experience gained from this first study, a second pilot plant unit has been constructed and tested





(Left) Fig. 1. Continuous slag wool filter for high temperature open hearth fume.

(Above) Fig. 2. Schematic diagram of continuous slag wool filter unit.

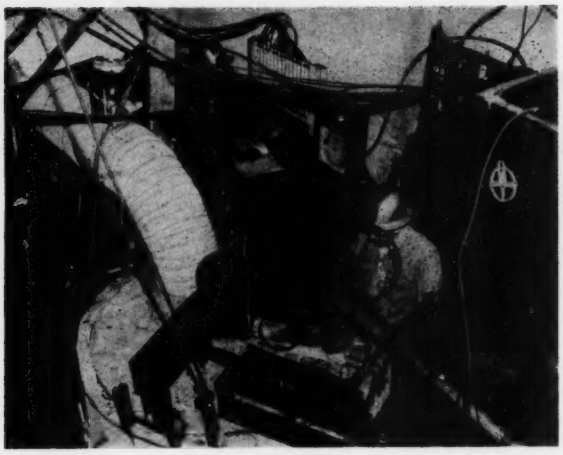


Fig. 3. Field installation of continuous slag wool filter pilot plant II.

Fig. 4. ➤ Used fiber reclaiming system for continuous slag wool filter pilot Plant II.

under identical conditions. Since space requirements are at a premium in an existing steel mill the new unit incorporates a circular disc to carry the filter bed in and out of the gas stream, instead of the former conveyor belt. A disc yields maximum useable area and operations take place over the whole surface, as opposed to a conveyor where a certain proportion cannot be used.

Description and Operation

The second continuous slag wool filter pilot plant consists of a 4 ft. diam. flat circular disc of 10 gage perforated sheet steel mounted on a vertical shaft (A) as shown in Fig. 1. Four rolled rings of 2 in. angle iron form the supports for a plenum chamber surrounding 3 quadrants of the disc. Two of the rings are placed adjacent to the disc to act as guides for the top and bottom surface of the outer edge. The other 2 rings act as plenum supports and contain cross bars for the upper and lower vertical shaft bearings. The fourth quadrant of the circular filter is left open for slag wool web forming and removing equipment. As in the original unit, a slurry of the slag wool fibers in water is used to form the filter bed. The slurry is introduced at tray (C), where it flows over the left edge and down onto the disc in the open quadrant. The majority of the water runs through the perforations in the disc into sump (E), leaving the fiber behind on the surface as a wet lap. As the disc slowly rotates, the fiber bed passes over a dewatering suction box (D) where the interstitial water is removed. The bed then advances into the hot gas plenum where it filters 750 cfm. of gas at temperatures over 900°F. Gas from the furnace enters and leaves the filter at (B) and (F) respectively.

Fig. 2 shows a schematic representation of the complete unit excluding the fiber and water cleaning stages discussed below. Slag wool slurry was made in the large reservoir shown at the bottom. Compressed air from manifolds bubbling up through the water caused the fibers to go into suspension and kept the concentration uniform throughout the tank. Slurry was pumped to the head tank above the filter by means of a small displacement pump consisting of a cylindrical drum with a vent valve at the top and a check valve at the bottom, alternately pressurized with compressed air and vented by means of a float inside the drum attached to the vent valve. Slurry ran by gravity to the filter unit from the surge tank, additional compressed air manifolds being used to keep the suspension uniform in this tank.

The second pilot filter unit was installed on the basement level of a 250 ton open hearth furnace, in the same location used for the Pilot Plant I field tests as shown in Fig. 3. (The general layout of the furnace, stack, and unit location has been given[4].) Open hearth furnace gas was drawn out of the flue leading to the waste heat boiler through an 8 in. probe with a mitered end. A connecting duct led from this probe to the filter inlet, and contained a Stairmand disc and the upstream sampling and temperature measuring points. Two tees and a damper were provided in this line to permit the gas to be passed through a rotary screw agglomerator prior to entering the filter. The overhead tank is shown on the right. Slurry flows down to the filter from the constant level tank through the line running from the lower right corner up into the center of the picture. Hot gas enters through the large line in the upper left, and leaves through the Venturi shown below this line, passing to a fan and stack out of the photograph on the left side. The air cylinder and gears in the center are used to drive the disc. Instrumentation for tests is shown in the background.

After passing over the dewatering suction box, the bed passed into the hot gas plenum where it rapidly dried and acted as a fiber filter for open hearth fume. As fume accumulated, resistance to gas flow increased and the disc was rotated sufficiently fast to maintain a constant resistance of 4 in. of water. When the bed had made ¾ of a revolution in the gas plenum, it emerged through multiple flap seals to the open quadrant. At

this point the used filter was removed from the disc by a series of small vertical plates mounted on a moving chain. Small clumps of used slag wool were *picked* by each of the plates and carried radially outward to a sluice leading to the fiber reclaiming equipment, shown in Fig. 4. They were washed down into an inclined tank (which also contained a compressed air manifold along the bottom). A sheet metal baffle at the center of the tank from about 4 in. above the bottom to above the top of the liquid surface divided the tank in half, except for the section near the bottom. The dirty slag wool filter was redispersed and separated into fibers in the first half of the tank (top of Fig. 4) by the agitation of compressed air. Water from the sump below the point of new filter formation, together with water from the dewatering suction liquid separator, entered the tank at this point. A current of water flowed from one half of the tank to the other underneath the baffle, carrying with it the reslurried slag wool fibers. Clumps of filter not dispersed continued to float on the liquid surface in the first half section.

After reaching the second half, the fibers were carried by the water over the lower rim of the tank onto an inclined screen. The screen was made of a 24 in. by 24 in. piece of aluminum perforated with ⅛ in. holes (on ½ in. centers) mounted on a steel frame, hinged at its lower end and free to rise and fall at the upper end. A cam shaft underneath the frame lifted and dropped the screen 380 times/min. As the slurry ran onto the screen, the dirty water ran through into a box below, leaving the fiber behind on the surface. The fiber slowly advanced down the screen due to the vibration and was continually flushed with small streams of clear water from a box above shown at the center in Fig. 4. All collected open hearth fume was washed from the fiber into the box below as well as short fibers, and whatever *shot* was left. Clean fibers were deposited in a tray at the end of the screen, from where they were returned to the main slurry tank by hand.

Liquid passing through the screen carrying iron oxide fume, lime, short slag wool fibers, *etc.* was directed through a short sluice to a clear water filter, shown at the bottom of Fig. 4. A 2 in. layer of slag wool fiber supported on an expanded metal screen (24 in. by 30 in.) at the bottom of a 2 ft. high sheet metal box filtered the dirty liquid by gravity. Water running through this filter was cleaned for reuse throughout the system. A clear-water pump sent it to: (a) the sluice leading from the filter unit to the wash tank; (b) the water box above the inclined vibrating screen; and (c) the main slurry tank. Water and slag wool were thus reclaimed and reused. Material remaining on the surface of the clear water filter was removed by hand about once or twice/hr.

A 12 in. rotary screw agglomerator as described previously[4] was also installed for use during field tests as shown in Fig. 5. It consisted of a 12 in. diam., 12 in. pitch, 7 ft. long conveyor screw mounted on a 3 in. diam. shaft. The screw was contained in a 16 gage metal cylinder about 12½ in. in diam., with a 1 in. wide slot in the bottom leading to a 6 in. diam. cylindrical collecting hopper running the full length of the screw. Six in. diam. tangential inlet and outlet ports were provided at the ends of the cylindrical casing just beyond the ends of the screw. Shaft pillow block bearings were fixed to the building framework, and the shaft was driven by a roller chain from a 900:1 gear reducer, which in turn was driven by a ½ HP, 1800 rpm. electric motor through a 4 step V-belt sheave. Speed could be varied from 1 rpm. to 10 rpm. in 4 steps. Additional 6 in. duct was provided to place the agglomerator in series with the filter unit.

Sampling and Analysis

The methods of sampling and analysis used during these studies were essentially the same as used during tests on the first pilot unit[3]. Particulate samples were collected on $1\frac{9}{16}$ in. diam. circles of 1106-B all glass filter paper held in stainless steel probes[2]. Inlet samples were taken 5 diam. downstream of the inlet Stairmand disc and outlet samples were taken at the entrance to the outlet Venturi. Initial and final filter weights were used to determine the concentration of total solids in the gas stream, and colorimetric analysis of the sample for iron permitted the determination of iron concentrations and iron to total solids ratio. Repetitive samples taken with 2 AISI samplers (as done in the first pilot tests) were obtained during the first 11 tests of this series, after which they were discontinued.

Gas temperatures were measured by thermometers and thermocouples located in the inlet duct just beyond the Stairmand disc, just above the filter bed, and in the outlet duct just before the Venturi meter.

Filter pressure loss was measured by a vertical manometer connected to piezometer rings on the casing of the filter. A continuous record was also obtained with a Bristol's Recorder in parallel with the manometer.

Gas flow in and out was measured by manometers connected to static taps across the Stairmand disc and on the Venturi.

Results of Continuous Filter Operation

Filter Unit Only

Sixteen tests were made on the second pilot plant operating continuously (without agglomerator) for a total period of 22 hr. Slag wool for these tests as well as all other tests reported here was obtained from the producer of *Mineralite* located at the Bethlehem Steel Company's plant.

A summary of results is given in Table I. Filter characteristics are indicated in columns 2 and 14. Thick-

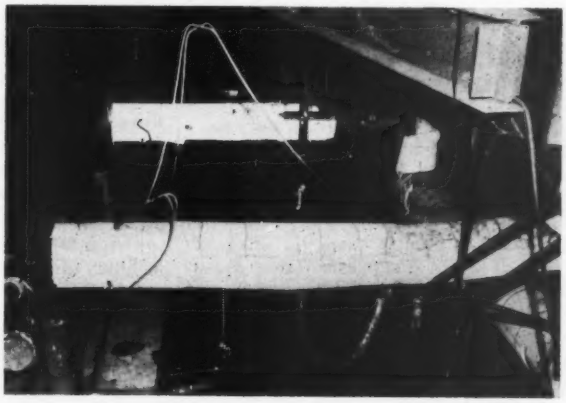


Fig. 5. ➤
Twelve inch diameter rotary screw agglomerator installed during field tests.

TABLE I

Summary of Field Results on Continuous Slag Wool Filter[a]—Pilot Plant II—Filter Only

Test No.	Filter Thickness Inch.	Filtering Velocity[b] fpm.	Average Resistance[b] Inch H_2O	Inlet Loading[c] gr./ft.^{3}		Efficiency % Weight		% Fe_2O_3 Inlet	Operating		Furnace Cycle[d]	Remarks	Filter Density lb./ft.^{3}
				Total	Fe_2O_3	Total	Fe_2O_3		Time Min.	Temp. °F.			
1	...	80	2.8	...	0.036	...	53	...	76	640	...		.
2	...	80	3.4	...	0.024	...	58	...	35	650	...		.
3	¾	75	3.9	...	0.008	...	48	...	57	660	E; C	No Rotation	3.7
4	¾	81	3.0	...	0.040	...	36	...	11	550	C		3.1
5	1¼	53	4.5	...	0.018	...	40	...	46	500	W	No Rotation	3.9
6	¾	85	3.8	...	0.040	...	57	...	67	700	M, H		4.9
10	...	91	3.5	...	...	...	...	...	56	650	E; C		...
11	1	97	2.9	0.148	0.022	46	60	15	95	750	M, H, O		2.7
12	¾	92	2.8	0.088	0.014	6	36	15	68	620	L		3.7
15	1	70	5.6	0.086	0.022	55	63	25	25	320	M		2.6
16	½	78	6.3	0.043	0.011	34	44	24	100	360	W, T, E; C, M		5.4
17	...	92	4.0	0.179	0.024	45	39	16	66	440	C, M		...
18	1¼	97	3.3	0.091	0.020	53	55	22	167	490	O, L, W		3.2
19	1	97	5.0	0.088	0.042	65	64	47	182	500	M, H, O, L		3.6
25	...	91	4.6	0.210	0.042	56	45	20	39	610	W		...
45	1	72	5.8	0.089	0.014	38	65'	15	221	640	E; C, M, H, O, L		6.4

a. Mineralite slag wool manufactured at Bethlehem, Pennsylvania.
b. At indicated temperature.
c. Volume STP, 70°F. and 760 mm. Hg.
d. Furnace cycle (heat) consists of phases: empty (E); charging (C); melt down (M); add hot metal (H); ore boil (O); lime boil (L); working (W); extra carbon (XC) or decarb (XD); tapping (T).

ness and packing density were measured from samples taken out of the filter web just before it emerged from the plenum. These samples were limited in number because the filter unit had to be stopped and cooled in order to gain access. It was not possible to remove samples as the bed emerged from the gas plenum because the picker removed the filter immediately adjacent to the plenum.

Filtering velocities and average filter resistance are given in columns 3 and 4, at the temperatures shown in column 11. Average inlet dust loadings (total and iron oxide) and average filtering efficiencies are indicated in columns 5 and 6, and 7 and 8, respectively. The relative amount of iron oxide in the inlet sample (assumed Fe_2O_3 from iron analysis) is shown in column 9. Operating time and furnace cycle are given in columns 10 and 12.

Discussion

Inlet dust loading

Average total inlet dust loading to the filter was 0.1 gr./ft.^{3} (STP), the same as was obtained during tests on Pilot Plant I. Average iron content was 22% during these tests, or slightly lower than previously found (35%).

Loadings greater than 0.2 gr./ft.^{3} were observed 4 separate times, during melting and working periods. Low loadings ($<$ 0.05 gr./ft.^{3}) occurred during the tapping, empty, and charging phases. In general, the loadings were related to the sequence of furnace operations in exactly the same manner as found in previous field tests[3]. The reasons for lower loadings on this furnace were thought to be: (a) non-isokinetic sampling at the probe in the furnace flue and (b) non-uniform aerosol concentration at the sampling point. In addition to these factors, it has been suggested that good furnace operating practice and favorable raw materials may also produce lower stack loadings.

Resistance

Average resistance for all runs reported in Table I is 4.1 in. of water at an average filtering velocity of 80 cfm./ft.^{2} and a temperature of 570°F. Resistance ranged from 2.8 to 6.3 in. of water, and velocity from 53 to 97 cfm./ft.^{2} Filter travel rate was varied slightly during operation to attempt to control resistance. (Average rotational rate is indicated in a subsequent section.) It is apparent from the range of resistances given above that the filter turned too slowly at some times, and too fast at others. Pressure control for automatic filter operation was provided, but not used during field tests because an investigator was usually standing by to make minor adjustments in speed control.

Original design considerations for a filter for open hearth fume have specified 4 in. of water as a desirable resistance. The second pilot unit will usually meet this requirement. During periods of maximum dust loading increased rotation can be accomplished by a higher slurry feed and automatic pressure actuation of disc rotation.

Efficiency

Average total efficiency from 9 tests in Table I is 44%; average iron oxide efficiency from 15 tests is 51%. Individual values varied from 2 to 89% (total) and 0 to 82% (iron oxide). Even with the improved peripheral seal between the moving filter bed and the stationary guide rails, efficiency has not been substantially increased over that found in Pilot Plant I. Because the lowered efficiency was thought to be due primarily to peripheral leakage while the disc is rotating, a series of tests were made with the disc stationary permitting the resistance to increase continuously. These tests are discussed below.

Life factor and packing density

The average filter thickness and packing density from Table I are 1 in. and 3.9 lb./ft.^{3}, respectively. Filters were formed on the disc without any direct help from the operator (except occasional variations in speed of disc rotation as discussed above) so that these characteristics of the filter represent *naturally* occurring values. Because the weight used to determine packing density represents the clean fiber plus some accumulated fume, it is likely that actual packing density was less than 3.9 lb./ft.^{3} Filter forming on Pilot Plant I was accomplished

TABLE II

Summary of Field Results on Continuous Slag Wool Filter—Pilot Plant II—Agglomerator and Filter in Series

Test No.	Filter Thickness Inch.	Filter Density lb/ft.³	Screw Inlet Velocity fpm.	Filtering Velocity fpm.	Average Resistance Inch H_2O		Inlet Loading gr./ft.³				Efficiency %, Weight				% Fe_2O_3 Inlet	Oper. Time Mins.	Inlet Temperature oF		Furnace Cycle
							Screw		Filter		Screw		Filter						
					Screw	Filter	Total	Fe_2O_3	Total	Fe_2O_3	Total	Fe_2O_3	Total	Fe_2O_3			Screw	Filter	
20	..	...	4200	56	0.91	7.3	0.073	0.023	0.044	0.012	38	48	48	30	34	70	910	230	O, L
21	1	2.0	4400	61	0.96	7.5	0.071	0.009	0.046	0.006	36	38	65	38	12	119	830	220	XD. W. T
22	1	2.2	5300	71	1.40	4.8	0.111	0.032	0.072	0.022	35	32	78	82	29	79	890	230	O, L
23	1	3.6	5200	72	1.30	5.1	0.074	0.016	0.046	0.010	36	36	55	42	20	188	860	260	W, XD, T, E; C, M
24	1	3.6	3700	52	0.87	7.6	0.074	0.016	0.050	0.011	31	30	56	57	21	86	810	220	H, O, L

Footnotes same as in Table I.

with a small amount of hand pressure on the web surface which increased packing density. A mechanical technique such as a roller or ram-actuated plate would be desirable to increase packing density by about 20% on Pilot Plant II.

No attempt was made to weigh the slag wool used during this period. Wool was added as required (determined by observation of slurry concentration) without recording weight of new wool added, so that no direct correlation is possible between the number of uses of a particular batch of wool and average resistance.

During testing of Pilot Plant I, wool was used on a batch basis and testing was suspended during washing of the fiber. Separation of *shorts* was not done directly, so that they accumulated in numbers during reuse, causing significant increases in resistance[3]. Continuous separation of short fibers and reclaiming of wool in the wool cleaning stage of Pilot Plant II prevented excessive *shorts* with associated increased resistance. (Information on wool requirement is included in the following section on combined agglomerator and filter performance).

Agglomerator and Filter in Series

With the experimental apparatus shown in Fig. 5, a series of 5 tests were made covering a total of 9 hr. operation of the screw agglomerator and filter in series. Results are indicated in Table II. By means of dampers on the filter inlet, gas from the furnace flue was passed initially through the screw agglomerator where turbulent, thermal and centrifugal forces cause particle aggregation and size buildup. The agglomerator outlet was connected to the slag wool filter inlet. Gas thus passed from the agglomerator to the filter.

Filter characteristics are shown in columns 2 and 3, and filtering velocity and resistance in columns 5 and 7, respectively, at temperatures shown in column 18. Screw inlet velocity (based on 6 in. diam. duct) and total screw resistance are given in columns 4 and 6 at temperatures given in column 19. The inlet loadings to the screw and filter (total and iron oxide) are given in columns 8, 9 and 10, 11. respectively, and corresponding screw and filter efficiencies in columns 12, 13, and 14, 15. Columns 16, 17, and 20 show the amount of iron oxide in the inlet sample (assumed Fe_2O_3 from iron analysis), total operating time, and furnace cycle, respectively.

Gas temperature entering the screw was frequently greater than 1000°F., and fell to about 500°F. at the outlet. Since this temperature drop appeared somewhat higher than expected, a separate study was undertaken in the laboratory to determine the effect on heat transfer coefficients of spiralling gas flow in the screw agglomerator[5].

Discussion

Inlet loading

Concentrations were determined at the inlet and outlet of the agglomerator and at the outlet from the filter unit by methods described above. Agglomerator inlet concentration averaged 0.08 gr./ft.³ total solids (average of 23% Fe_2O_3), and the filter inlet loading (also the agglomerator outlet loading) averaged 0.05 gr./ft.³ total solids. The maximum loading to the screw of 0.16 gr./ft.³ occurred during addition of hot metal and the minimum value of 0.03 gr./ft.³ during a period with the furnace empty. Loadings to the agglomerator were slightly lower than those reported above for the filter only. Average loadings to the filter with the agglomerator in series were reduced to about half as much as with the filter alone. This is apparently due to the slightly lower average loading into the agglomerator, and a positive collection efficiency in the agglomerator.

Resistances

Average total resistance of the agglomerator was 1.1 in. of water at 4500 fpm. inlet velocity and 820°F. inlet temperature.

Average filter resistance was 6.5 in. of water at 62 cfm./ft.² filtering velocity. The average temperature at the filter bed of 230°F. was considerably lower than that obtained with the filter unit alone (570°F.). Presumably the lower temperature is less effective for drying the damp slag wool filter, leading to a higher average resistance and lower filtering velocity than with the filter only.

It was observed many times during this period that increasing the rotational speed of the filter unit to attempt to lower the resistance actually caused higher resistance. If the temperature of the incoming gas is too low the bed does not dry rapidly, and a slower rotational speed is desirable. On the other hand, collected material accumulating on the filter causes resistance to rise and requires a faster rotational speed. Using a water slurry of slag wool to form the filter requires that a reasonable drying temperature be maintained in the filtered gas.

Efficiency

Collection efficiency of the agglomerator-filter combination averaged 60% based on total weight and 50%

TABLE III

Slag Wool Consumption and Filter Rotation Rate—Pilot Plant II

Test No.	Cumulative Time Min.	Wool Used Lb.	Cumulative Number of Strokes[a]	Filter		Wool Use[b] Tons/day		Filter Rotation Rate Min./rev.
				Thickness Inch.	Density Lb/ft.³	A	B	
19k	182	..	...	1	3.6	...	10	13
20d	252	..	...	...	...	...	...	...
21d	326	60	...	...	...	8.8	...	...
21g	371	..	...	1	2.0	...	5.7	13
22e	450	30	80	1¼	2.2	11.6	7.4	14
23h	579	..	240	1	3.6	...	3.4	40
23k	638	30	350	1¼	2.8	8.1	8.7	15
24f	734	15 (est)	492	1	2.8	7.5	5.8	18

a. Each stroke is 1/19th of a revolution.
b. Wool use rate, tons/day (24 hr.), for 50,000 cfm. of gas: A. Based on lb. of wool actually used (Col. 3) containing up to 50% *shot;* B. Based on filter characteristics (Col. 5, 6) and rotation rate (Col. 9), washed wool, used 8 times.

based on iron oxide. Individual total values ranged from 25 to 90%, and iron oxide values from 0 to 88%. The filter efficiency was improved with the agglomerator in series, although it is difficult to assign this improvement solely to the agglomerator. Side effects such as a damp bed and lower gas temperature and filtering velocity were present.

Test 22 (Table II) was conducted continuously for an hour and 20 min., giving satisfactory results for most of this period. Collection efficiency varied from 66% to 90% at filter resistances of 3.8 to 6.4 in. of water and velocities of 62 to 78 cfm./ft.^{2} The efficiency and filtering velocity are slightly lower, and pressure loss slightly higher than original design specifications for the open hearth filter pilot plant. This test illustrates the variation in results due to the experimental conditions, and indicates that with minor modifications we can achieve the desired operating conditions.

Life factor and packing density

Average filter thickness and packing density for tests of the combined agglomerator-filter unit are 1 in. and 2.8 lb./ft.^{3}, respectively. Here, the *naturally* occurring packing density is substantially lower than the 5 lb./ft.^{3} indicated by laboratory tests as desirable for filtration, and a roller or ram acting on the filter surface would assist in achieving satisfactory values.

During tests 19 through 24 observations were made on the amount of slag wool used and the rate of rotation of the filter disc as shown in Table III, columns 1 through 4. Wool was added when required by visual observation of the slurry and bed forming process, the criteria being when the slurry was too dilute, excessive time was required to form a filter bed. Based on experience with Pilot Plant I[3], slurry concentrations were not made too thick since this seemed to cause a coagulation and *balling-up* of the wool, which made it useless as a filter. Samples of the slurry obtained at different periods have indicated that an average concentration of 0.1% was maintained. Most of the operation was made with slurry concentrations about $\frac{1}{10}$th as high as the probable maximum limit water will carry before coagulation becomes a problem.

From the total amount of wool used (Table III, column 3) and elapsed time (column 2) it is possible to calculate the rate of wool consumption. This has been done in column 7 and the figures given are predicated upon a full furnace volume of 50,000 cfm. of gas (50,000/750, multiplied by the amount used in the pilot plant) for a 24 hr. day. Average wool use is 8.5 tons/day, as received including *shot* (slag spheres). For a 250 ton open hearth furnace about 8.5 tons of slag wool would be required, based on the actual consumption of a 750 cfm. pilot plant operated for a test period of 12.2 hr. (*i.e.*, 734 min.). If *shot* runs as high as 50% of the wool as received, by weight, then actual fiber consumption is about 4.25 tons/day which agrees reasonably well with estimates from previous field and laboratory studies of 1 to 3 tons/day.

Another estimate of wool consumption can be made from the measured filter characteristics, thickness and packing density (columns 5 and 6) and the filter rotation rate (column 9). By calculating the amount of wool actually on 7.5 ft.^{2} of the filter and applying the rotation rate, wool use rate/min. for the 750 cfm. pilot plant can be prorated to that required for a full furnace volume. To arrive at a conservative estimate, wool has been assumed to be recycled 8 times, as found in the previous pilot plant study[3]. Average wool consumption rate from this calculation (shown in column 8) is 6.8 tons/day.

If the assumption of 8 times wool recycle is correct, then this figure indicates that (by comparison with 8.5 tons/day from actual use rate) the slag wool used during these tests had about (6.8/8.5) 20% *shot*. If, on the other hand, it is assumed that *shot* comprises 50% by weight of the wool, then the number of recycles or reuses of the wool must have been on the order of 13 times to give a net consumption of useable wool of 8.25 tons/day. Unfortunately, no actual measurements were made of the *shot* content of wool used during these tests. Wool used in the laboratory from the same producer has been checked a number of times and it appears that on the average this wool has a shot content of 25%.

Sulfur Gas Removal

During field evaluation of Pilot Plant I preliminary tests indicated that slag wool was removing gaseous sulfur compounds which seemed to cause fiber attrition. Further investigation in the laboratory[4] showed that Mineralite fiber removed 26% SO_2 gas and 69% H_2SO_4 mist. Filters exposed to acid mist appeared to deteriorate in a manner similar to that observed during field studies.

Sulfur dioxide samples were taken during continuous operation of Pilot Plant II. Through the cooperation of the Bethlehem Steel Company, Industrial Hygiene Department, samples were analyzed by three different methods to evaluate the most useful one with results as reported in Table IV.

The method indicated as I_2-KI is described by Pearce and Schrenk[6], the fuchsin method by Stang, Zatek and Robson[7], and the $BaSO_4$ method is done by turbidimetric estimate of the precipitate.

Average inlet sulfur dioxide concentration by each method is 66 ppm. I_2 KI, 62 ppm. fuchsin, and 98 ppm. $BaSO_4$, indicating that the I_2-KI and fuchsin methods give similar results. Average positive collection efficiency by each of the 3 methods is 39% I_2-KI, 72% fuchsin, and 13% $BaSO_4$. For all positive tests average removal is 49%.

After the first 4 preliminary tests with I_2-KI, the testing was done serially as indicated by numbers in the last column of Table IV. Simultaneous up- and downstream samples were taken for each of the three methods in succession. In test No. 1, the I_2-KI method was used first (line 5), then the sample for fuchsin analysis was obtained (line 9), and finally the $BaSO_4$ sample was taken (line 13). This procedure was repeated in tests 2, 3 and 4. Comparing concentration and efficiency results on the basis of test number does not give a strong correlation between methods of analysis. A comparison of average inlet concentration indicates that the specific fuchsin method yields the lowest values while the non-specific I_2-KI and $BaSO_4$ methods give results that are somewhat higher. Based on these tests the slag wool filter removes about 50% of SO_2 from an average of 75 ppm. in open hearth furnace gas, while performing its primary function as a particulate filter.

TABLE IV

Sulfur Dioxide Removal by Continuous Slag Wool Filter Operating on Open Hearth Fume

Filtering Velocity fpm.	Average Resistance Inch. H_2O	SO_2 Concentration PPM. Inlet	SO_2 Concentration PPM. Outlet	Efficiency %	Temperature °F.	Analytical Method For SO_2	Test #
90	7.2	38	56	..	750	I_2-KI	Preliminary 1
80	7.1	56	13	73	800	"	" 2
90	6.3	36	25	30	820	"	" 3
110	4.8	24	14	42	830	"	" 4
110	3.2	43	65	..	850	"	1
100	3.9	74	102	..	850	"	2
90	5.9	189	125	34	900	"	3
110	3.3	68	58	18	840	"	4
100	3.9	45	19	59	860	Fuchsin	1
100	4.0	94	38	61	880	"	2
80	6.8	70	8	89	900	"	3
100	3.2	43	10	78	775	"	4
90	4.1	55	59	..	740	$BaSO_4$	1
100	4.6	176	235	..	920	"	2
110	4.1	90	78	13	870	"	3
100	4.2	72	77	..	830	"	4

Results of Stationary Filter Operation Filter Unit Only

Average collection efficiency for open hearth fume in Pilot Plant II was about 50% when tested during continuous filter formations. This was not substantially better than obtained in Pilot Plant I. To obtain a better edge seal in the new unit, the periphery of the disc rode in a circular track formed by two rolled angle iron rings. As the filter bed was formed fibers were overlapped onto the upper surface of the top ring so that as the filter rotated the fibers could assume whatever form was required to keep gas from leaking past the filter.

Since filter efficiency with this method of sealing was not significantly higher than in previous tests, it was suggested that possibly a moving seal of such simple construction was inadequate. To attempt to eliminate the effect of peripheral leakage due to rotation, a series of tests were made

TABLE V

Stationary Slag Wool Filter Tests on Open Hearth Fume—Pilot Plant II—Filter Only

Filter Thickness Inches	Filter Density Lbs./ft.³	Filtering Velocity fpm.	Resistance Inch. H_2O Initial	Resistance Inch. H_2O Final	Inlet Loading gr./ ft.³ Total	Inlet Loading gr./ ft.³ Fe_2O_3	Efficiency % Total	Efficiency Weight Fe_2O_3	% Fe_2O_3 Inlet	Operating Time Mins.	Operating Temp. °F.	Furnace Cycle	Test No.	Remarks
1½	3.5	78	7.6	10.8	0.122	0.034	75	71	30	15	700	L	32	Wet
...	...	65	12.9	9.4	..	..	..	..	..	11	630	W	33	"
1¼	5.5	85	9.0	9.6	0.095	0.015	71	71	16	10	800	"	"	"
...	...	77	3.5	4.2	0.044	0.004	50	11	8	12	670	C	34	Dry
1¼	4.0	74	4.3	9.9	0.311	0.013	91	72	4	12	780	"	"	"
...	...	79	4.5	8.1	0.087	0.031	91	89	35	20	720	L	35	"
1½	3.4	58	8.7	10.4	0.105	0.032	98	95	31	11	760	"	"	"
...	...	78	2.3	8.5	0.310	0.045	88	80	15	12	680	M	36	"
1½	3.2	65	8.7	9.6	...	...	..	..	..	6	780	"	"	"
...	...	80	1.1	2.0	0.055	0.004	79	21	8	15	680	W	39	"
...	...	85	2.3	4.6	0.051	0.004	53	13	8	16	810	W, T	"	"
...	...	84	5.2	7.2	0.036	0.003	74	..	8	10	830	T	"	"
1½	3.6	85	7.2	7.5	...	...	..	..	..	8	845	T, E	"	"
...	...	79	1.1	3.1	0.147	0.027	42	48	18	14	700	M, H	40	"
1½	3.0	68	3.3	10.0	0.217	0.032	87	82	14	11	780	H	"	"

Footnotes same as in Table I.

TABLE VI

Stationary Slag Wool Filter Tests on Open Hearth Fume—Pilot Plant II—Agglomerator and Filter in Series

Test No.	Filter Thickness Inch.	Filter Density lbs/ft.³	Screen Inlet Velocity fpm.	Filtering Velocity fpm.	Resistance Inch. H_2O			Inlet Loading gr./ft.³				Efficiency % Weight				% Fe_2O_3 Inlet	Oper. Time Mins.	Inlet Temp. °F.		Furnace Cycle	Remarks
					Screw	Filter		Screw		Filter		Screw		Filter							
					Total	Initial	Final	Total	Fe_2O_3	Total	Fe_2O_3	Total	Fe_2O_3	Total	Fe_2O_3			Screw	Filter		
27	...	...	7000	100	1.1	6.4	5.7	0.105	0.036	0.091	0.039	13	..	63	66	35	20	950	320	W	Wet
"	...	...	5600	79	0.7	6.4	7.9	0.077	0.025	0.065	0.024	15	4	83	69	33	10	950	310	"	"
"	1	3.8	4400	65	0.5	8.2	9.4	...	...	...	...	..	..	..	..	..	10	825	270	"	"
28	...	...	5400	81	0.7	8.2	5.3	...	...	...	...	..	..	..	..	..	6	700	200	E	"
"	...	...	8400	120	1.6	3.8	3.2	0.029	0.010	0.031	0.014	..	..	79	78	36	11	975	330	C	"
"	...	...	7800	112	1.5	3.1	3.2	...	...	...	...	..	..	..	..	..	25	1060	380	"	"
"	...	...	7600	108	1.3	3.4	4.2	0.075	0.016	0.056	0.014	25	17	71	63	22	17	1095	380	C, M	"
"	...	...	6100	88	0.9	4.8	7.9	...	...	...	...	..	..	..	..	..	15	1000	340	C, M	"
"	1¼	3.9	4800	71	0.4	8.9	10.4	0.082	0.020	0.056	0.023	32	..	95	90	25	11	840	270	M	"
29	...	...	3800	62	0.8	9.5	7.7	...	...	...	...	..	..	..	..	..	15	610	210	O	"
"	...	...	6600	92	0.9	6.6	7.6	0.188	0.138	0.190	0.143	..	..	98	97	74	10	930	280	"	"
"	1½	3.8	4100	60	0.4	9.2	11.0	0.163	0 093	0.153	0.153	6	..	97	97	57	12	825	260	O, L	"
30	...	...	3600	53	0.4	11.1	8.6	...	...	...	...	..	..	..	..	..	16	700	200	XC, W	"
"	1	4.6	6400	88	0.9	7.0	9.4	0.137	0.097	0.128	0.088	6	9	94	92	71	12	880	250	W	"
31	...	...	4300	64	0.4	11.1	7.8	...	...	...	...	..	..	..	..	..	20	730	220	T, E	"
"	...	...	7500	109	1.2	7.1	5.4	0.022	0.004	0.020	0.002	8	42	62	18	18	20	990	350	E	"
"	...	...	6600	98	1.0	5.4	5.7	...	...	...	...	..	..	..	..	..	14	980	350	C	"
"	1	4.9	5200	77	0.8	6.1	10.2	0.080	0.006	0.074	0.007	7	..	97	86	7	20	930	315	"	"
41	...	...	5300	73	...	1.3	2.8	...	...	0.124	0.023	..	..	81	69	18	15	800	200	C	Dry
"	...	...	5600	73	...	2.9	6.8	...	...	0.099	0.022	..	..	90	76	23	14	890	215	"	"
"	1½	4.6	3800	53	...	7.5	10.0	...	...	0.110	0.016	..	..	93	76	15	11	790	200	"	"
42	...	...	5700	78	...	1.1	2.4	...	...	0.094	0.019	..	..	75	76	20	13	800	200	O	"
"	...	...	5800	73	...	2.5	4.2	...	...	0.064	0.013	..	..	94	74	21	13	930	210	"	"
"	...	...	5600	72	...	4.3	6.8	...	...	0.068	0.013	..	..	89	78	33	10	930	220	"	"
"	1½	2.6	4500	59	...	7.2	9.0	...	...	...	...	..	..	..	..	..	19	880	210	"	"
43	...	...	5700	80	...	2.1	2.8	...	...	0.083	0.047	..	..	92	87	57	13	770	200	M	"
"	...	...	5900	79	...	2.9	5.2	...	...	0.046	0.046	..	..	91	91	100	13	860	210	"	"
"	...	...	4900	65	...	5.5	8.2	...	...	0.080	0.038	..	..	97	94	47	10	860	210	"	"
"	1¾	3.0	4100	56	...	8.4	8.8	...	...	...	...	..	..	..	..	..	4	820	200	"	"
44	...	...	5800	80	...	2.0	5.0	...	...	0.091	0.051	..	..	94	90	56	13	780	200	L	"
"	1½	3.2	4600	63	...	5.5	9.8	...	...	0.062	0.017	..	..	98	92	27	12	810	200	"	"

Footnotes same as in Table I.

with stationary filter beds. A clean bed was run into the unit in the usual manner before gas was admitted from the furnace flue. Preliminary tests were made with the filter as formed with its residual moisture. When hot furnace gas was admitted in these cases a certain amount of drying occurred causing the resistance to fall during the first part of the test, then as fume accumulated the resistance rose, which made analysis of results rather difficult. Subsequent tests were made by first drawing room air through the filter until the bed dried and resistance fell to a constant value. The unit was then tested with the bed held stationary, allowing resistance to rise as required. Filtering velocity was held relatively constant during the test within the limits of the fan capacity.

Table V presents results of stationary filter tests without the agglomerator. The average filtering velocity and resistance is given in columns 3, 4, and 5, and average inlet loading and efficiency in columns 6, 7, and 8, 9, respectively. Test numbers 32 and 33 (column 14) were with initially wet filters, the remainder (34, 35, 36, 39, and 40) with filters that had been dried on room air. Tests covered approximately all cycles of a furnace heat (column 13).

Average filtering velocity was 76 cfm./ft.² and resistance with initially dry beds rose from 2.5 to 9.5 in. of water during an average length of run of 29 min. When the furnace was being charged (test 34) the filter ran for 24 min., resistance increasing from 3.5 to 9.9 in. of water; while melting (test 36) it ran for 18 min., going from 2.3 to 9.6 in. of water; while melting and during the hot metal pour (test 40) it ran for 25 min., going from 1.1 to 10.0 in. of water; during the lime boil (test 35) it ran for 31 min., going from 4.5 to 10.4 in. of water; and finally at the end of the heat, while working, tapping, and empty it ran for 49 min. (test 39) going from 1.1 to 7.5 in. of water.

Average collection efficiency of the 5 dry runs was 75% (based on total weight concentration) which is substantially higher than the value obtained with the filter operating continuously (59%). Stationary efficiencies ranged from 42 to 98% (total weight basis) with half being about 90% or higher.

Agglomerator and Filter in Series

A summary of stationary filter tests on the combined agglomerator and filter unit is given in Table VI. This table corresponds to Table V with the addition of columns 4, 6, 9, 10, 13,

14, and 19 which contain the operating results pertaining to the screw agglomerator.

In the combination unit average filtering velocity of initially dry beds was 70 cfm./ft.^{2}, resistance rising from an average of 1.6 to 9.4 in. of water during an average length of run of 38 min. During the charging cycle (test 41) the unit ran 40 min., resistance rising from 1.3 to 10.0 in. of water; during melt down (test 43) it ran 40 min., going from 2.1 to 8.8 in. of water; during an ore boil (test 42) it ran 45 min., going from 1.1 to 9.0 in. of water; and during a lime boil (test 44) it ran 25 min., going from 2.0 to 9.8 in. of water.

In general, the length of run (even with initially wet filters) is related to amount of material that the furnace is emitting. For example, during tapping, empty and charging cycles (test 31) a period of low dust and fume production, an initially wet filter ran for 74 min., resistance falling during drying from 11.1 to 5.4 in. of water (during 40 min.) and then rising as fume was collected to 10.2 in. of water (during 34 min.). Tests 29 and 30 represent high loading conditions, the filter operating for 37 and 28 min., respectively. This pattern of resistance change is observable in all wet runs, but there is some doubt as to whether all started from the same datum resistance condition since residual moisture was not determined in all cases.

Average collection efficiency for the 4 dry runs was 90% (based on total weight concentrations) with a range from 75 to 98% and 9 of the 11 runs about 90% or greater.

Discussion

Resistance

Since filters were held stationary a criterion of 10 in. of water was used as maximum allowable filter resistance as contrasted to 4 in. of water used during continuous operation. Average resistance of the filter only (stationary) was 6.5 in. of water with a range from 1.1 to 10.8 in. With the agglomerator in series the average resistance of the filter was 6.3 in. of water, ranging from 1.3 to 11.0 in.

Rate of resistance increase

Because the filters were stationary in the above tests, it is possible to determine the resistance increase due to fume accumulation. The rate has been calculated by taking the change in resistance of any test or observation in Tables V and VI which show an increase and dividing by the time interval during the change. For example, in Table VI, test 27 (the first 3 lines) the resistance fell from 6.4 to 5.7 in. of water during 20 min. as the filter dried out, then rose from 6.4 to 7.9 and from 8.2 to 9.4 in. of water as fume accumulated during 10 min. in each case. The rate of increase is then calculated only from the second and third observations as 0.150 and 0.120 in. of water/min., respectively. The average of all values for the stationary filter only is 0.216 in. of water /min. and for the combination agglomerator-filter is 0.163 in. of water/min. This means that the agglomerator is actually producing a lower resistance increase in the filter. If clean filter resistance is 2 in. of water and a 2 in. rise is permitted then the stationary filter alone will operate 9.3 min. (on the average) before reaching 4 in. of water and under the same conditions the agglomerator-filter combination will operate 12.3 min. (If the upper resistance limit is extended to 6 in. of water then the filter alone will operate 18.6 min. and the combination unit will operate 24.6 min.) This implies that use of the agglomerator will extend fiber usage about 30% or that 30% less fiber is required. The average resistance across the screw agglomerator was 1.0 to 1.5 in. of water to achieve this change in filter performance.

Efficiency

As indicated above, average efficiency was on the order of 90% with stationary slag wool filters, which is approximately the value found in laboratory tests. This seems to be fairly conclusive evidence that a stationary bed will collect greater than 90% of the open hearth fume and that continuous slow rotation causes reductions in amount collected because of the difficulty of making a tight sliding seal. Future pilot plant units will include plans for an operating cycle of relatively long dwell while the filter bed is being made and rather rapid transfer between positions so that the time for bed movement can be kept to a minimum. It is also expected that the next pilot unit will have provision for some type of positive liquid seal.

Life factor and packing density

At the conclusion of most tests of stationary filters, both with and without the agglomerator, samples were taken of the used filter bed and of the clean web still remaining in the open quadrant. Average clean filter thickness and density for the filter unit only was 1.64 in. and 2.9 lb./ft.^{3} Average dirty thickness and density was 1.43 in. and 3.7 lb./ft.^{3}, respectively. If the *average* clean filter was compressed to 1.43 in. its packing density would increase to 3.3 lb./ft.^{3} so the net increase in weight of the filter due to accumulated fume is 0.4 lb./ft.^{3} or (0.4/3.3) 12%. Based on an assumed reuse of wool 8 times, the total fume recovered is 96% of filter weight or 96 lb. of open hearth fume/100 lb. of wool. Average increase in resistance for dry filters was found to be 2.5 to 9.5 or 7 in. of water, giving a life factor ($B/\triangle p$; 96/7) of 14%/in. of water increase in resistance. For an allowable resistance increase of 2 in. of water[3] the fume recovery factor B becomes 28%, which represents a reasonably good check on the experimentally determined value from tests of Pilot Plant I (34%).

Average clean filter thickness and density for tests on the combined agglomerator-filter was 1.50 in. and 2.75 lb./ft.^{3}: average dirty values were 1.56 in. and 3.35 lb./ft.^{3}. Net fume accumulated was 0.60 lb./ft.^{3} or (0.6/2.75) 22%, if the change in filter thickness is assumed negligible. With an assumed life or recycle of 8 times the fume recovery is increased to 176%, or 176 lb. of fume/100 lb. of slag wool. The resistance of initially dry filters increased on the average from 1.6 to 9.4 or 7.8 in. of water. Filter rating factor ($B/\triangle p$) is therefore (176/7.8) 22%/in. increase in resistance. Allowing 2 in. of water increase in resistance, the fume recovery factor becomes 44%, which is about 22% higher than that found in the first pilot plant tests (34%).

The increase in filter rating factor from 28 to 44% is another direct indication that the rotary screw agglomerator is performing as intended. Larger particle size should increase the amount of fume recovered/unit weight of slag wool used, and this appears to be the case. The average increase in fume recovery factor B with the agglomerator in series with the filter is 36%, or about the same as the improvement found from the independent analysis of the rate of increase of filter resistance (30%).

TABLE VII

Screw Agglomerator[a] — Impinger[b] Efficiency Studies

Test No.	Screw Inlet Velocity[c] fpm	Temperature °F		Resistance "H2O	Up	Loading[d], gr./ft.[3]		% Fe_2O_3	Efficiency % Impinger			Impinger #		Furnace Cycle[e]
		Inlet	Outlet			% Fe_2O_3	Down		Up	Down	Overall	Up	Down	
A	7100	1250	650	1.7	0.34	13	0.34	6	89.2	94.4	0	1	2	W
B	7400	1250	660	1.6	0.19	38	0.13	2	93.5	95.1	30	1	2	T
C	7400	1250	640	1.7	0.40	14	0.31	9	95.9	94.5	24	1	2	HM, O
D	7200	1270	660	1.6	0.32	19	0.18	15	98.9	99.2	43	1	2	O
E	7200	1270	660	1.6	0.48	29	0.34	11	99.6	99.7	30	2	1	L
F	7500	1220	660	1.6	0.32	47	0.23	18	98.8	98.3	27	2	1	W

a. Screw rotating at 1.67 rpm.
b. Large impinger with 100 cc. H_2O followed by 1106B glass filter paper.
c. At temperature indicated in third column.
d. Volume at STP, 70°F., 760 mm. Hg.
e. Furnace cycle symbols same as shown in Table I.

Rotary Screw Agglomerator Tests Efficiency for Particulate Removal

Sampling and analysis

Samples of inlet and outlet dust concentrations for the rotary screw agglomerator were taken with the same probes used on the filter unit. The upstream sample was taken 5 diam. after a Stairmand disc but the downstream sample was taken in a rather short section of the outlet pipe where a Stairmand disc could not be used.

Analysis of samples was done by weighing all-glass filter papers before and after use and by determining the iron content in the collected sample.

In order to duplicate laboratory test conditions on a 3 in. agglomerator[4] a settling chamber was placed in the outlet line of the 12 in. agglomerator used for field tests. A 55 gal. drum was provided with 6 in. collars on top and bottom; a 6 in. diam. flanged collar and a plate were added half-way on the side; and a hinged baffle was put inside to partially close the area of the drum. This chamber was put in the outlet with its major axis horizontal, the top of the drum became the inlet and the bottom the outlet; the side cleanout port was at the bottom. Several samples of this chamber were also made, as described above, with the baffle up (open area) and down (partially closed area).

Discussion

Results of a series of tests on screw agglomerator collection efficiency for operation without baffle chamber, and with the chamber, baffle up and down, indicate that average collection efficiency of the screw agglomerator alone was 40% based on total weight loadings, and 33% based on iron oxide loadings. With the baffle chamber after the agglomerator, average efficiency was 41% (total) and 32% (Fe_2O_3) with baffle up, and 43% (total) and 41% (Fe_2O_3) with the baffle down. Baffle chamber efficiency averaged about zero percent with baffle up and down. The largest majority of results for the chamber indicated a slightly higher concentration coming out of the chamber than going in, which indicates a relatively low efficiency for the chamber and a possible sampling error.

The average screw agglomerator efficiency from all tests (including those with the screw in series with the filter unit) was 36% (total weight). Based on laboratory tests[5] and because there was a possibility of some air in-leakage to the screw through the long seams at the bottom (between the screw and the hopper), it is more realistic to assume that actual efficiency of the screw may be somewhat lower. Laboratory tests of a 6 in. agglomerator have indicated that efficiency is about 10%.

Heat transfer studies also showed that the large temperature drop found in the field agglomerator (500 to 600°F.) must have been partly due to leakage of cold air into the unit. It is more conservative to assume that the agglomerator efficiency is about 10 to 15% and the higher average value found during field studies was due to air leakage and a possible error in the downstream sample.

Agglomeration

Sampling and analysis

In order to check the agglomeration of submicron particles in the field unit, efficiencies of two types of size-selective dust collectors were investigated when operated on fume from the inlet and outlet of the agglomerator. Standard impingers were placed at the outer end of short probes and gas samples were drawn with these by means of the usual sampling probe placed after the impinger. Material passing the impinger was collected on 1106-B all-glass paper held in the probes. Analysis of these samples for total weight and iron oxide was done in the usual manner (by first evaporating the water from the impinger samples).

Aerotec cyclones (3 in. in diam) were placed at the end of probes leading to the inlet and outlet ducts of the agglomerator and high volume samplers containing Type S pleated filters were used to draw gas samples through the cyclones, the filter being used to collect the material passing the cyclone. A quantity of room air was also drawn in through an orifice meter after the cyclone, lowering the gas temperature into the high volume sampler to protect its motor windings. Analysis of these samples was made by weighing material collected in the cyclone hopper and on the pleated filter (iron analysis of the material was also made in the usual way).

Discussion

The factors tending to cause particulate agglomeration in dynamic gas streams have been presented in a previous report[8]. If open hearth fume has been caused to agglomerate to a significantly larger size, then collecting devices that are sensitive to particle size may be expected to show an improved efficiency on fume from the outlet of the agglomerator, over that from the inlet. To test the screw agglomerator by these indirect methods, (and to check laboratory results[4] in the field) standard impingers at sonic velocity were used to sample up- and downstream of the agglomerator with results as indicated in Ta-

ble VII. In tests A, B, D, and E, downstream impinger efficiency was greater than upstream efficiency, indicating some particle size increase. Test C and F showed slightly higher efficiency for the inlet impinger. Average inlet impinger efficiency was 96%, average outlet was 97%, which leads to the belief that particulate agglomeration is occurring. This is particularly true when the net positive collection efficiency of the agglomerator is considered (26% average in these tests) for this collection is undoubtedly due to centrifugal action which will affect mostly the larger particles. If the larger particles are removed in the screw then the outlet aerosol would be finer (without agglomeration) yielding lower collection efficiency in the outlet impinger. An increase in downstream impinger efficiency, even when larger particles are removed, gives evidence of particulate agglomeration.

Results of a similar study on the efficiency of cyclone collectors on the up- and downstream fume of the agglomerator is given in Table VIII. Cyclone efficiency was determined on the agglomerator itself in tests A and B. Upstream cyclone efficiency was higher than downstream efficiency in both of these tests. Tests C, D, and E were run on the inlet to the agglomerator and outlet from the settling chamber and indicated a significantly higher efficiency for the downstream cyclone. The fact that dust concentrations determined from the downstream unit are consistently higher than those determined upstream makes these results of doubtful value, and points to a possible sampling error. On the basis of the cyclone efficiencies themselves, it would appear that agglomeration is occurring in the screw. Considering the higher downstream concentration makes this conclusion liable to criticism. There is a possibility of some particulate agglomeration occurring in the screw in these tests but it is not conclusive.

The combined results for both impinger and cyclone efficiency studies would seem to indicate that the rotary screw agglomerator is producing particulate agglomeration, as theoretically concluded, and as found in laboratory studies[4].

As a direct measure of agglomeration, inlet and outlet fume samples were taken on electron microscope targets with the electrostatic precipitator described previously[8]. Preliminary analysis of these samples at 12000X magnification (on an RCA EMT Electron Microscope) has indicated that inlet samples have a count median diam. of 0.214 μ with a geometric standard deviation of 2.06. Downstream samples have a diam. of 0.295 μ and a deviation of 2.06, which would indicate some particulate agglomeration. Unfortunately, the resolving power of the electron microscope used was not sufficient to delineate all of the fine particles that previous work has shown to be present[8]. Further analysis on a more powerful microscope will be done to firmly establish the particle sizes.

Conclusions

1. Field tests of the second continuous slag wool pilot plant operated normally on open hearth fume have indicated an average collection efficiency of 50%, ranging from 0% to 89%.

2. A rotary screw agglomerator preceding the unit gives an average efficiency for the filter of about 55% with a range from 25% to 90%.

3. Stationary slag wool filters gave an average efficiency of about 90%.

4. Minor redesign of the unit to provide a positive seal and sequential indexing should give uniform collection efficiencies greater than 90%.

5. Resistance of the normally operated continuous filter was controlled by varying rotation speed and was maintained most of the time at about 4 in. of water without difficulty. Occasionally fume emission from the furnace exceeded the ability of the filter forming process and resistance rose to greater than 6 in. of water.

6. Average resistance of stationary filters was about 6.5 in. of water ranging from an initial value of 1.2 in. of water to about 10 in. of water finally.

7. Stationary filters operated on the average about 30 min.

8. The rate of resistance increase for stationary filters was 30% lower when the screw agglomerator was included in series with the filter unit. Use of the screw agglomerator should extend fiber usage about 30%.

9. Average resistance of the screw agglomerator was on the order of 1.5 in. of water.

10. Web packing density and thickness should be more closely controlled during formation.

11. Observations on the 750 cfm. pilot plant indicate that about 4 tons/day of slag wool would be required for an average 250 ton open hearth furnace which is about the same as calculated from previous field tests.

12. Automatic washing and reclaiming of slag wool fibers needs some investigation to determine the optimum conditions for maximum cleaning and minimum fiber breakage.

13. Average dust loading to the filter was about 0.1 gr./ft.^{3} or essentially the same as found in studies on Pilot Plant I.

TABLE VIII

Screw Agglomerator[a] — Aerotec[b] Cyclone Efficiency Studies

Test No.	Screen Inlet Velocity[c] fpm	Temperature — °F. Inlet	Outlet	Settling Chamber Outlet	Resistance "H$_2$0	Loading[d] — gr./ft.^{3} Up	% Fe_2O_3	Down	% Fe_2O_3	Efficiency % Up	Down	Overall	Unit	Furnace Cycle[g]
A	7500	1160	610	440	1.7	0.14	58	0.068	54	4.8	2.5	52	Scr.	W
B	7400	1180	625	460	1.8	0.21	50	0.065	46	2.7	2.0	69	Scr.	W
C	7500	1250	660	460	1.7	0.10	61	0.13	61	15.0	31.6	..	Set. Ch.[e]	O
D	7400	1260	645	450	1.8	0.15	58	0.17	59	4.2	8.9	..	Set. Ch.[e]	L
E[f]	7400	1200	645	450	1.8	0.10	65	0.28	58	6.7	13.3	..	Set. Ch.[e]	W

a. Screw rotating at 1.67 rpm.
b. Size 1, Design 3, rated volume 85 cfm. at 4000 fpm. inlet velocity, followed by High Volume Sampler.
c. At temperature indicated in third column.
d. Volume at STP, 70°F., 760 mm. Hg.
e. Baffle down.
f. Rapping probes to dislodge dust.
g. Furnace cycle same as shown in Table I.

14. Mechanical operation of the unit and auxiliary equipment was generally good with minor modifications in design being suggested by the field experience.

Acknowledgements

Field studies discussed in this report were conducted at the Saucon Division of the Bethlehem Steel Company's Bethlehem, Pennsylvania Plant and were materially aided by contributions of manpower and material. Tests were made possible by the cooperation of Dr. A. D. Brandt and Messrs. Arbogast, Enders, Koch, Chapman and Whitman. Members of the Combustion, Maintenance and Open Hearth Production Departments also contributed time and effort to the successful completion of this study. We would like particularly to thank Mr. N. E. Whitman and his associates in the Industrial Hygiene Department of the Bethlehem Steel Company for their analysis of sulfur dioxide samples.

Much invaluable technical assistance was rendered by our associates at the Harvard Air Cleaning Laboratory, particularly Edward F. McKenna and Robert A. Gussman who aided in design, construction and testing of the unit, and Edward Kristal who assisted in field studies.

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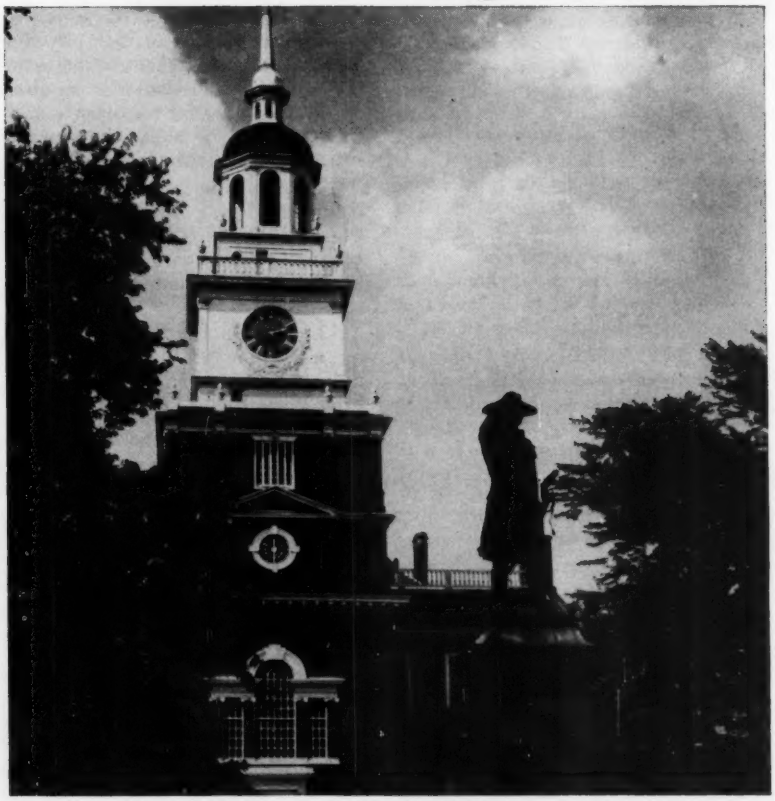

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An Analysis of Diffusion Measurements*

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The scientific program of the Geophysics Research Directorate of the Air Force Cambridge Research Center includes studies of the diffusion of aerosols and gases in the atmosphere. These investigations are being conducted along experimental as well as theoretical lines. Some of the research work is being done by university contractors, some of it by in-house personnel.

In 1954 a team of meteorologists of the Massachusetts Institute of Technology, working at the Round Hill Field Station in South Dartmouth, Massachusetts, began the development of a tracer technique for eventual use in field studies of diffusion.(1) The developed technique was field-tested in experiments conducted at Round Hill in late 1954. A series of diffusion experiments followed in 1955.

The purposes of this paper are (1) to present a method of analyzing such diffusion data and (2) to show the results when this method is employed in the analysis of the 1955 data.

Description of Experiment

The experiments were conducted over a fairly flat, grassy area from which bushes and scrub growth had been removed. Upwind of the experimental site the cleared area extended to about 500 ft. from the source. Upwind of this area came the natural scrub growth followed in turn by a wooded area.

The tracer used in the diffusion experiments was sulfur dioxide gas. In each experiment the gas was emitted continuously and at a steady rate for 10 min. The emission rate varied, however, from experiment to experiment, ranging from about 5 g./sec. to 10 g./sec. The gas was emitted vertically at a height of 1 ft. above ground.

Ten-min. samples of the gas were collected on 3 semi-circular arcs having the gas source as center. The arcs were 50, 100, and 200 m. from the gas source. Impinger bottles were attached to posts spaced at 3-degree intervals on each of the 3 arcs. The sampling height was 2 m. above ground. The sampling rate was 1.5 *l.*/min.

In addition to the determination of average concentration at each of the 183 sampler positions, measurements were made of mean wind speed and temperature at 4 heights between 1.5 and 12 m. above ground. High-speed wind fluctuation data were collected with heated thermocouple-bivane anemometers at a height of 2 m., while time series of wind direction were obtained with wind vanes at the same height.

Data Analyzed

The distribution of concentration (X) along each arc takes on the characteristics of a frequency distribution, the concentration acting as a frequency and the 3-degree interval centered on any post acting as the class-interval of the distribution. Some of these distributions are irregular in appearance, having more than one mode. However, a number of the distributions are unimodal and fairly symmetrical, the majority of these being approximately Gaussian in character. In the investigations conducted to date by the author, only those experiments which produced nearly Gaussian distributions have been studied in some detail. Such distributions were found during both lapse and inversion conditions. In the present paper, however, the analysis is confined to inversion cases having nearly Gaussian distributions of concentration along the arcs.

For each of the inversion cases, Gaussian curves were fitted to each of the concentration distributions. These curves provide, in each case, a peak or maximum concentration (Xp) along each arc as well as a standard deviation [σ(X)] of the concentration distribution. Since concentration at any point in the field is assumed to be proportional to the rate of gas emission (Q) and inversely proportional to the wind speed (U), a type of normalization is provided by considering $\frac{XU}{Q}$ instead of X.

In addition to $\frac{XpU}{Q}$ and σ (X), a meterological parameter is employed in this analysis. This parameter is the standard deviation of the wind direction (σ_A).

Analysis of Results

In this paper the experimental data will be used to express the adjusted concentration at the 2-m. height in terms of polar coordinates (ρ, θ) and σ_A. In addition, the area within an isopleth of concentration will be expressed in terms of $\frac{XU}{Q}$ and σ_A.

At the outset it may be pertinent to discuss the attempt to express these quantities in terms of σ_A, particularly since σ_A is not a quantity which normally appears in the theoretical work in this field. In an unpublished paper, Cramer and Record, employing the same Round Hill data, have shown that $\frac{XpU}{Q}$ and σ(X) are rather strongly related to the standard deviation of the wind direction, σ_A. However, for small values of σ_A, such as exist particularly during inversion conditions, σ_A is approximately equal to the lateral gustiness component,

$$\frac{\sqrt{v'^2}}{U}$$

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* Presented at the 50th Annual Meeting of the Air Pollution Control Association held at St. Louis, Mo., June 2-6, 1957.

(1) The technqiue which was finally developed will be described by Drs. Record and Cramer in another paper entitled, *Preliminary Analysis of Project Prairie Grass Diffusion Measurements.*

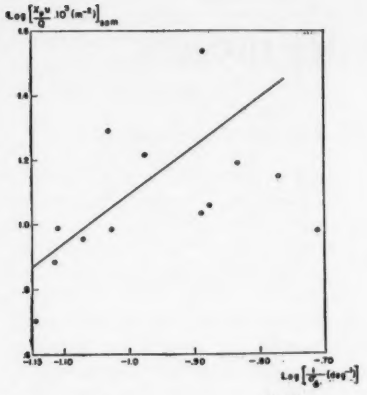

Fig. 1. Relationship between $\frac{X_pU}{Q}$ at 50 m. and $\frac{1}{\sigma_A}$.

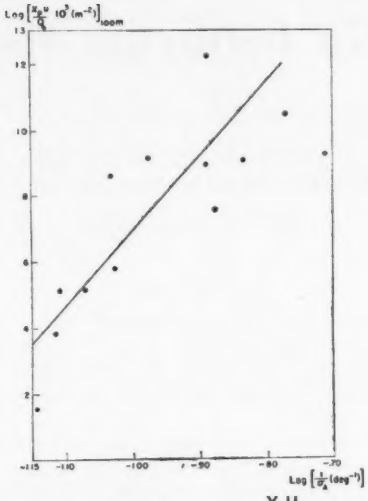

Fig. 2. Relationship between $\frac{X_pU}{Q}$ at 100 m. and $\frac{1}{\sigma_A}$.

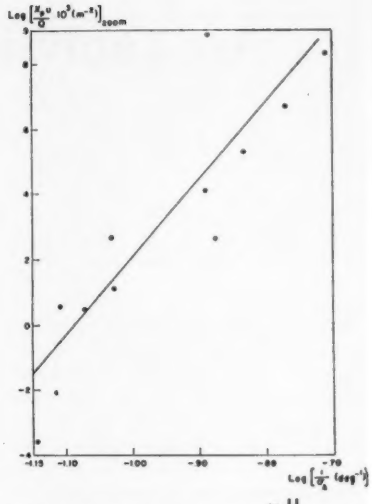

Fig. 3. Relationship between $\frac{X_pU}{Q}$ at 200 m. and $\frac{1}{\sigma_A}$.

This component, however, does appear in the literature, *e.g.*, as a factor in the lateral diffusion coefficient appearing in Sutton's work. Therefore, the attempt here to express $\frac{XU}{Q}$ and the area within an isopleth in terms of σ_A is not entirely novel. Of the 2 quantities, σ_A and the lateral gustiness component, both of which can be computed from data collected during the Round Hill experiments, σ_A calls for simpler measurement and computation procedures.

Since the concentration distributions along the arcs are nearly Gaussian in the cases studied, the Gaussian model,

$$\frac{XU}{Q} = \frac{K}{\sigma(X)} \exp \left[- \frac{(\rho\theta)^2}{2\sigma^2(X)} \right] \qquad (1)$$

is employed in this analysis. Here K is constant for a given arc and $\frac{K}{\sigma(X)}$ is the adjusted peak concentration on an arc.

Fig. 1-3 illustrate the relationship between $\frac{X_pU}{Q}$ and $\frac{1}{\sigma_A}$. The logarithms of the 2 variables are plotted in these figures. Fig. 1 shows the relationship for the 50 m. arc. The line shown is a least-squares line in the determination of which the data of 3 experiments, shown by open circles, are omitted because other evidence indicates that the axis of the plume may have been beneath the 2-m. height of the samplers. In Fig. 2, prepared to show the relationship for the 100 m. arc, the data from 2 experiments are omitted, for the same reasons, in the determination of the line. In Fig. 3, prepared to show the relationship for the 200 m. arc, data from all 3 experiments were utilized in the determination of the line.

The 3 figures suggest $\frac{X_pU}{Q}$ is inversely proportional to σ_A raised to a power varying from less than 2 for the 50 m. arc to more than 2 for the 200 m. arc. An average value of 2 was assumed for the entire 200-m. range, it being recognized, at the same time, that this assumption is a crude one.

In addition to depending on σ_A, $\frac{XpU}{Q}$ depends on distance from the source (ρ). From the data shown, the dependence was found to be best expressed by the relationship,

$$\frac{XpU}{Q} = \frac{348}{\rho^{1.44}\sigma_A{}^2}, \qquad (2)$$

where $\frac{XpU}{Q}$ is in m^{-2}, ρ is in meters, and σ_A is in degrees.

Fig. 4-6 illustrate the relationship between σ (X) and σ_A for the 50, 100, and 200 m. arcs. In each figure, the

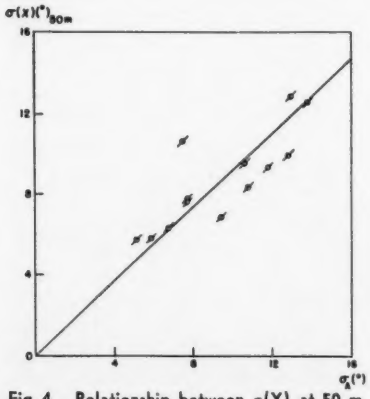

Fig 4. Relationship between σ(X) at 50 m. and σ_A.

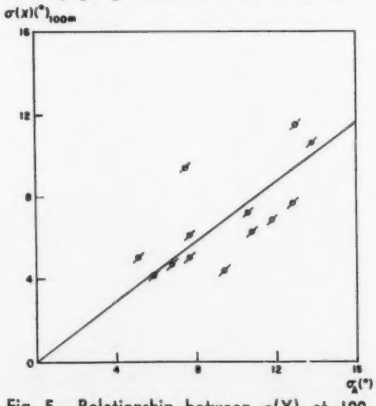

Fig. 5. Relationship between σ(X) at 100 m. and σ_A.

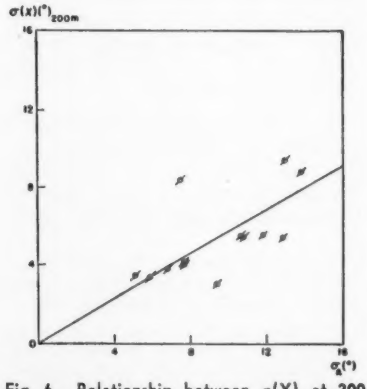

Fig. 6. Relationship between σ(X) at 200 m. and σ_A.

line shown was drawn from the (0, 0) point through the point representing the means of the 2 variables. On a given arc, $\sigma(X)$ appears to be proportional to σ_A, the proportionality factor being a function of distance from the source. The relationship was found to be

$$\sigma(X) = .0626\ \rho^{.6\frac{1}{2}}\ \sigma_A \qquad (3)$$

where $\sigma(X)$ and ρ are in meters and σ_A is in degrees.

Substitution of *(2)* and *(3)* in *(1)* gives the relationship,

$$\frac{XU}{Q} = \frac{348}{\rho^{1.4\frac{1}{2}}\ \sigma_A{}^2} \exp\left[- \frac{(\rho\theta)^2}{.0078\ \rho^{1.28}\ \sigma_A{}^2} \right] \qquad (4)$$

where $\rho\theta$ is in meters.

From *(4)* it is possible to compute the area enclosed within an isopleth of $\frac{XU}{Q}$. Explicit integration provides the expression

$$A_C = \left(\frac{41.4}{\frac{XU}{Q}} \right)^{1.13}\ \sigma_A{}^{-1.26}, \qquad (5)$$

where A_C is the computed area in m^2, $\frac{XU}{Q}$ is the adjusted concentration in m^{-2} and σ_A is in degrees.

The shape of a typical isopleth of adjusted concentration is shown in Fig. 7. The particular one shown has the value of the adjusted peak concentration on the 200 m. arc. There is a similarity between this shape and the shape of a leaf of the lemniscate, a geometrical figure expressed as,

$$\rho^2 = a^2 \cos 2\theta,$$

where a is the length of the leaf. Use of the more general form,

$$\rho^2 = a^2 \cos n\theta, \qquad (6)$$

permits variation of the width of the leaf through variation of the parameter n.

The modified lemniscate *(6)* was used in this analysis to approximate isopleths of adjusted concentration. In this study the isopleth sought was the one having the value of $\frac{XpU}{Q}$ on the 200 m. arc. In the lemniscate, then, a was taken as 200 m. For each experiment, however, it was necessary to determine n. This was done by determining at what value of θ the ordinate of the Gaussian distribution on the 100 m. arc was equal to $\frac{XpU}{Q}$ on the 200 m. arc. With a fixed and the intersection of the lemniscate and the 100 m. arc determined, n was found from *(6)*.

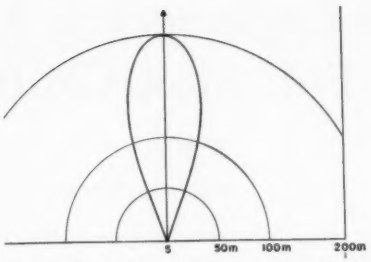

Fig. 7. Typical isopleth having the value of $\frac{X_pU}{Q}$ at 200 m.

The modified lemniscate is particularly useful in computation because the area of the leaf, here denoted as an observed area (A_o), is found to be,

$$A_O = \frac{a^2}{n}.$$

Since the distributions along the arcs were not perfectly symmetrical in the experimental data analyzed, the area of the left portion of the leaf (Fig. 7) was not equal to the area of the right portion. Therefore the area of the leaf was actually found from

$$A_O = \frac{a^2}{2}\left(\frac{1}{n_L} + \frac{1}{n_R} \right), \qquad (7)$$

where the subscripts refer to the left and right portions of the leaf respectively.

In Fig. 8, the computed areas found from *(5)* are compared with the observed areas found from *(7)*. The line $A_C = A_O$ is shown. The scatter about this line is not large, indicating reasonably good agreement between the computed and observed areas.

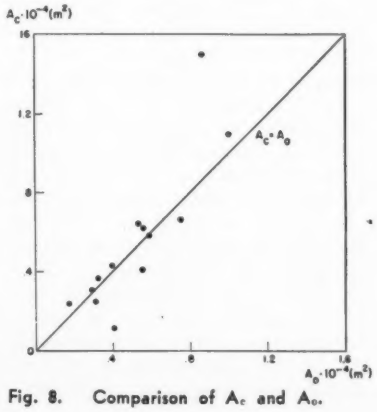

Fig. 8. Comparison of A_c and A_o.

Concluding Remarks

An empirical method of expressing adjusted concentration in terms of (ρ, θ) coordinates and the standard deviation of the wind direction has been presented. In addition, the area within an isopleth of concentration is expressed in terms of the same standard deviation. Since the formulae are based on smoothed relationships over a range of 200 m., extrapolation to greater distances is not recommended.

In applications where the standard deviation of wind direction is known, the relationships presented here are recommended for use until such time as advances in theory or additional experimental data either modify them or render them obsolete. In some applications, however, the standard deviation may have to be predicted. The degree to which this parameter can be predicted may then determine the utility of the relationships presented. The predictability of this parameter is the subject of another research study under way.

Since the upwind fetch at Round Hill was not uniform and since the range was limited to 200 m., it was clear even in 1954 that more extensive field measurements over uniform, level terrain would eventually be necessary. Such a field program was finally conducted near O'Neill, Nebraska, in the summer of 1956. The program is referred to as Project Prairie Grass.

Organized by the Geophysics Research Directorate, the program included participation by the Massachusetts Institute of Technology[2], the Texas A & M Research Foundation, the University of Wisconsin, the Air Weather Service and the Air Force Cambridge Research Center. It is hoped that the diffusion measurements and the associated meteorological data collected during Project Prairie Grass will be published in 1957 and that their publication will fill a void which has long existed in the literature of atmospheric diffusion.

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[2] A preliminary analysis of the diffusion measurements made by the Massachusetts Institute of Technology during Project Prairie Grass appears in the paper cited above.

Chemical Engineering Aspects of Air Pollution Control*

by

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The Chemical Engineering aspects of Air Pollution Control have not been recognized fully until recent years. This resulted from the emphasis placed by the designers of control apparatus on the elimination of smoke and particulate matter from gaseous effluent. This emphasis was aided further by the enactment of legislative standards aimed at regulation of the more obvious polluting effluents, namely, those from combustion processes. These standards set up maximum allowable smoke density and fly ash emissivities.

The public demand for regulation of other air pollutants was not present except in isolated areas, chiefly around copper, lead and zinc smelters. In these areas, sulfur dioxide and arsenic fumes caused major damage to crops and livestock. Lawsuits, in which substantial monetary damages and even injunctions to cease operations were demanded, forced companies to investigate and install ways and means for the elimination of these polluting substances.

As the chemical and petroleum industries grew in size and number, people living in the neighborhood of such plants would register more frequent and louder complaints with the increasing incidence of obnoxious, nauseating, acrid fumes and gases discharged from these operations.

News reports of such tragedies as Donora, the London smog and pollution alerts in Los Angeles would spark public and legislative interest into enacting more inclusive ordinances. Today's modern laws, besides containing restrictions as to the amount of particulate matter or smoke discharged into the air, also prohibit the emission of gases, mists or fumes that may be toxic, obnoxious or are a nuisance.

This growing pressure to eliminate the discharge of all types of pollutants presents a tremendous challenge to the Chemical Engineer.

There are 2 groups in our modern civilization that contribute to contamination of the atmosphere: One is industry and the other is the public.

Industry is conscious of the necessity for minimizing or eliminating the venting of any chemical waste from its operations. It does an excellent job in recovering economically valuable gaseous wastes. However, there are areas in which more work will have to be done, chiefly those that may be termed *residual wastes* and are not economical to recover.

Manufacturers are finding it necessary to seek efficient means for eliminating the discharge of this type of pollutant in order to either reduce plant maintenance resulting from corrosion and wear of equipment or to establish good public relations with the community in which they work.

The problems associated with controlling the emission of pollutants by the public are complicated by the fact that usually the amounts discharged by an individual are small, discontinuous and dilute. Further, there is no incentive to install control equipment.

The process design is the first place where air pollution control should be attacked. The engineer who is well acquainted with potential sources of atmospheric pollution should be brought in on the process design as soon as the laboratory turns the research project over to the pilot plant and design groups. In some instances, it may be profitable for this engineer to work along with the research team.

I think it would be well to review the more common sources of air pollution directly attributable to chemical reactions or chemical manufacturing operations. First, let us look at industrial sources and see what chemical engineering design features are required to minimize pollution.

Perhaps one of the more difficult types of pollution to control is that resulting from general ventilation of plant areas and equipment. Plant area pollution results from careless housekeeping; poor maintenance of motive equipment, chiefly stuffing boxes and seals on pumps and agitators; improper ventilation of atmospheric reaction vessels and the venting of storage tanks.

In controlling pollution derived from poor housekeeping and maintenance of equipment, the means are quite obvious, namely prevention.

The design of reaction vessels must take into consideration either or both of 2 factors, to be specific, the case where a gas is evolved from a reaction and second where no gas is formed, but the reactants have a sufficiently high vapor pressure that they volatilize readily.

If tanks are operated at atmospheric pressure, the air moving equipment must be designed to accommodate the maximum rate of gas emission plus an amount of outside air sufficient to maintain a negative pressure up to 1 in. water when the maximum amount of gas is being evolved. This will be equivalent to indraft velocities, under these conditions, across all vessel openings of between 100 to 200 ft./min.

When reaction vessels are charged with dusty powders or liquids of high volatility, the amount of air required to prevent vapors or dusts seeping into the plant must be such that a minimum indraft velocity of 75 ft./min. is obtained across all openings. Where reactions occur at superatmospheric pressure, the relief valve and control system must be sized to accommodate the maximum rate of gas evolution. The vent lines from these vessels should be connected to appropriate scrubbing, absorption or adsorption equipment that will remove any polluting material.

*Presented at the 50th annual meeting of the Air Pollution Control Association, held at St. Louis, Mo., June 2-6, 1957.

Another major source of organics in the atmosphere is storage tanks. The amount of solvent loss through storage tank *breathing* and the alternate filling and emptying of tanks can be appreciable. It has been reported that the oil industry loses between 6 and 12 million barrels of crude oil each year by evaporation.

Distillation units can be an important source of air contamination. The main point of discharge is the condenser. The efficiency of condensation will determine the amount of polluting material vented. The concentration and total quantity can be calculated knowing vapor pressures, terminal temperature of the cooled vapors and column throughput.

In designing condensers, consideration must be given to the fact that small amounts of non-condensable gases, such as air, have a marked effect on coefficients of condensation. In addition to the thermodynamic design of the condensing unit, a good mechanical design of the system to prevent mist formation and carry over of mist or droplets with the non-condensable stream is a necessity.

When a distillation unit is operated at atmospheric pressure, a well designed vent condenser using chilled water or a refrigerant would be invaluable in reducing the emission of the volatile overhead product. If the material boils over 125°C., a condenser, if properly designed, may be sufficient to condense 99% or better of the overhead vapors.

In some few cases where the overhead substance has a penetrating odor at very small concentrations (measured in ppm.), it may be necessary to install scrubbers or adsorbers in the vent.

The air contamination problems associated with vacuum tower operation stem directly from the discharge of the vacuum pump or vacuum steam jet to the atmosphere.

Air leakage into a vacuum system becomes important in determining the amount of air pollution that may result. As the air leakage increases, the dew point of the vapor becomes lower, consequently the cooling liquid's temperature must be reduced correspondingly if the last traces of vapor are to be removed.

Another place to look for sources of air pollution is the hot well vapors or the exhaust from the final stage steam jet. The hot well should be enclosed and vented through a condenser and it would be desirable also to condense the exhaust from the steam jet and pass the non-condensables through a scrubber or adsorber.

Up to this point, we have discussed only vapor or gaseous pollutant sources from processing equipment. In some portions of the chemical industry, mixing, grinding and drying operations are performed in which solid particles may be carried by an air stream into the surrounding atmosphere. The project engineer must be on the lookout for these sources, as dusts, mists and fumes can be highly irritating. A knowledge of the solubility, wetability and particle size distribution is most important in selecting the optimum type of control apparatus. In some cases, the exhaust gases are at an elevated temperature and normal filter materials will not stand up. In such instances gas cooling will be required.

The classes of apparatus most often used for the solution of dust problems comprise filters, scrubbers, impingement and inertial separators, and electrostatic precipitators.

The next important phase of air pollution control is the process to be used for its conrol. Once the sources of pollution have been recognized and every effort has been taken to prevent the escape of pollutants into the general atmosphere, the engineer must then look for and design equipment to remove these substances from the vent stream. These have been indicated as including adsorption, extraction, absorption and incineration. Chemical engineering plays an important role in the design and selection of the appropriate control method.

One of the tools available to the Chemical Engineer in combating air pollution is that of *Absorption*. Closely akin are Scrubbing and Extraction. The basic data needed to design equipment in this group are mass transfer rates between the absorbing liquid and the absorbed vapor, diffusion in the gas and liquid phases and area of contact between liquid and gas. Contact between liquid and gas may be accomplished by the use of impingement sprays, jet scrubbers, bubble plate, sieve plate and packed towers.

Because it is important in the design of air pollution control equipment to minimize pressure drop, the equipment used most often fall into the impingement spray, jet scrubber and packed tower group.

To design these units, such fundamental information as equilibrium relations, diffusivity constants and the function correlating mass transfer rates with height of transfer units must be available. In many instances, these functions may be calculated from existing data or from experimentally determined correlations.

One of the main problems facing the designer is that the concentration of gases usually found in air pollution work is quite small, often under 10 mol. %. Consequently, in order to minimize equipment size, the absorbent having the greatest solubility of the gas should be used. In some instances, however, it is cheaper to use water as the absorbent, even though solubility of the gas is low, since the resulting effluent may be thrown away. The engineer is cautioned that by so doing, he may be solving one type of pollution problem by creating another one—stream pollution.

The chemical reactivity of the pollutant is most important. In one case, an organic chemical possessing a very unpleasant odor was thought to be acidic in nature. Dilute caustic soda was selected as the absorbent without effect. After much investigation, it was found that the chemical gave a basic reaction. The problem was solved by using a waste sulfuric acid stream to absorb the gas and eliminate the discharge of odor. A caustic soda tower followed the acid scrubber to eliminate the venting of any acid mist.

When solvents are used, means must be provided for stripping the absorbed gases from them, otherwise the cost of operations becomes excessive. A typical example of this is the recovery of hydrogen sulfide, using diethanolamine solutions as the solvent.

In general, there is a sufficient amount of equilibrium data available for the solubility of many of the common gases in water. A number of absorption studies have been made for other systems where the gas streams are pure or fairly concentrated. But, there has been little quantitative data published for the absorption of gases and vapors from dilute streams. More work along this line should be undertaken. These data will prove helpful to the engineer by permitting a more economical design of equipment. In addition, more meaningful concentration limits can be set up in the various codes that could be obtained without

excessive capital and operating costs being required.

The diffusivity of gases through gas and liquid films often may be calculated from known information on other systems or by the use of accepted correlations such as Gilliland's empirical equation.

Scrubbers, particularly the spray or jet type, are used frequently for fume and mist control. The engineering design principles for this operation are based on impingement, coalescence of micron sized particles, direct condensation or wetting of the mist or fume particles by the liquid. Direct condensation methods are very effective when high boiling vapors of fatty acids, tar acids, etc. must be removed from vent streams.

We find that there are little published design data available to the engineer that are suitable for calculating the efficiency of scrubbers of the spray or jet type. Such facts as the relationship between spray volume and transfer units; the effect of surface tension, as it relates to the wettability of fumes and mass transfer rates are still far from being in a state where a predictable design can be made.

A knowledge of particle wettability is extremely important in determining how effectively a unit will remove a fume or foglike mist from a gas stream. At present, high energy impingement scrubbers or electrostatic precipitators are used for this operation. Power costs and large scrubbing liquid requirements present problems that in some instances make control of air pollutants by these means very unattractive.

When the concentration of pollutant in the vent gases approaches a value of 2 vol. % or less, a most attractive means for removing almost 100% of the contaminant is by *Adsorption*. Even when concentrations are measured in ppm., properly designed adsorption apparatus will remove substantially all of the contaminant. One of the major uses of adsorption is the recovery of solvent vapors using such adsorbents as activated charcoal, activated alumina or silica gel.

Basically, adsorption processes work by causing condensation of the vapors at a temperature higher than that indicated by their concentration. In this operation, latent heat is released. Since the efficiency of adsorption decreases with increasing temperature, it is important to install methods for removal of the latent heat.

Reactivation or desorption of the adsorbent is usually accomplished by heating the adsorbent and subsequently condensing the desorbed vapors in a surface condenser. The recovered condensate, in most instances, must be purified further, usually by distillation.

The affinity of an adsorbent is not the same for all substances. As a result, the vapor having the greater intensity of adsorption will displace other vapors of lesser intensity that may have been adsorbed previously. This phenomenon is the basis of hypersorption separation processes used in the petroleum industry.

As the design of all air pollution control equipment requires that low pressure drops be designed into the unit, the gas velocity through a deep bed of granular adsorbent is low of the order of 20 to 120 ft./min. As an alternate to deep beds, higher gas velocities may be used if a parallel flow system is designed using shallow beds.

The rate of adsorption, or its reciprocal the contact time, is a function not too well known to engineers. Up to the present, there are few correlations that will permit the calculation of this factor based on such physical characteristics as pore size, pore area, activity as related to molecular structure, *etc.* As a result of the dearth of this type of design information, each new problem must be submitted to the laboratory for tests.

As the requirements for air pollution control become more stringent, adsorption processes for the removal of low concentrations of air contaminants may increase, chiefly because of their high efficiency of recovery and simplicity of operation.

Another method for disposing of organic materials is by combustion. Nearly pure combustible streams, such as occur in petroleum refining operations, may be burned in a flare or used as a fuel. As the concentration decreases, we find that a point is reached where the vent gases are too dilute to burn. In this case, an incinerator type of furnace must be designed.

The main requirement in the successful combustion of air contaminants is to heat the flammable compound above the temperature of combustion. In most instances, the gases must be heated to a uniform temperature in the range of 1200 to 1400°F.

Passing very dilute gases through the zone of combustion, as in the case where they are used as secondary air, will not necessarily insure that all molecules have reached the combustion temperature and consequently been destroyed. The proper design of combustion chambers, to provide both radiation surface and sufficient residence time in contact with the radiant surface, will increase the probability of complete oxidation.

One answer to the requirements of high flame temperature and uniform heating of the flammable molecules is Catalysis. The use of catalysts for reducing the activation temperature of chemical reactions is well known. Combustion processes are just as susceptible to catalytic activation as are other reactions. As an example, platinum catalysts will cause combustion at temperatures as low as 500°F.

In order to have a self-sustaining flame, the minimum concentration of gas in air must be equal to the lower limit of flammability. This concentration varies from 1 to 10 vol. %, depending on the substance. A distinct advantage to catalytic oxidation is that a self-sustaining reaction will result even when the combustible material concentration is down to one quarter of the lower limit. When concentrations fall below this point, it is not difficult to provide sufficient heat to raise the gas temperature to the 500 to 550°F. range required for operation of these catalytic units. Further, it is reasonable to assume, that since catalytic reactions are dependent on molecular adsorption on a surface, if the contact time is sufficiently long all the flammable molecules will be oxidized.

A disadvantage to the platinum type catalyst is its susceptibility to poisoning by contact with heavy metals (lead, zinc, arsenic), the halogens and silicones. The selection and invention of stable oxidation catalysts that are immune to poisoning is a challenging problem to the designers of catalytic combustion equipment.

Most air pollution is derived from combustion processes, whether it be on the large scale of a public utility generating station or that discharged from the individual automobile, truck or bus. And aside from smoke and fly ash, the largest single pollutant is sulfur dioxide.

There are 2 ways to attack the problem of sulfur dioxide; one is to eliminate the sulfur in the fuel by extraction or chemical reaction and the other is to remove the sulfur di-

oxide from the combustion gases by scrubbing.

In the case of solid fuels, it is almost impossible to remove sulfur and similar potential air pollutants prior to use. Hence, the only effective means of control is to scrub the flue gases. A good deal of work has been done in this country, by the TVA and the U. S. Bureau of Mines, as well as in England to devise economical systems for stripping the sulfur dioxide from flue gases. These methods have included in the main, scrubbing with sodium and ammonium sulfite solutions forming the bisulfite and subsequent stripping by heat. Sulfuric acid may be made by oxidation using ozone or the normal catalytic processes. Sulfur dioxide can be recovered economically as sulfuric acid from gas concentrations as low as 5%. Below that, the large volumes of gases that must be handled make the usual recovery processes economically unattractive.

The problem is somewhat simpler when liquid fuels are used. The petroleum industry is installing new methods, such as hydrodsulfurization for removing mercaptan sulfur from fuel oil and residual fractions. The sulfur is recovered as hydrogen sulfide which is then converted into sulfur.

Burning of liquid fuels in internal combustion engines poses another problem resulting from the incomplete oxidation of the hydrocarbons. Part of this may be solved by redesign of the engines themselves, improvement of carburetion, and changes in method of fuel injection. Another method that is being promoted is the use of catalytic combustion units. The chemical engineering problems met in the development of these units are substantially the same as those enumerated in our discussion of catalytic incineration. The problems of mechanical stability of the catalyst and susceptibility to lead poisoning are great and must be solved so that the overall cost of the unit will be small and maintenance will not be noticed by the average automobile owner.

There is one other point in which chemical engineering functions that has not as yet been mentioned, namely instrumentation. Without proper instrumentation, the accurate measurement and control of pollutants is not possible. Various methods for continuously recording gas concentrations include gas spectroscopy, adsorption, conductance, infra-red spectrophotometry and chemical reactions. In many instances, the method used for instrument analysis results in the formation or measurement of an electric current.

For example, the Titrilog type measures an oxidation-reduction potential. It is used for such gases as sulfur dioxide, hydrogen sulfide, mercaptans, etc. A conductivity cell instrument may be used for any ionizable water soluble gas. Hot wire resistance is used to measure flammable gases. In all these units means must be used to remove all interferring gases. These methods may be chemical or physical.

The analytical methods for measurement of polluting gases are in their infancy and offer a great opportunity for future development.

In this review, only the highlights of the place chemical engineering holds in the field of air pollution control and measurement have been touched on. There is much work still to be done, particularly in the removal of low concentration contaminants cheaply. The engineer must consider in his process design the most likely sources of air contamination and make provision at this time for its control. The cost of equipment and of process operation is of prime concern to the engineer who has the responsibility for the elimination of not only industrial air pollution, but also that arising from the daily activity of all.

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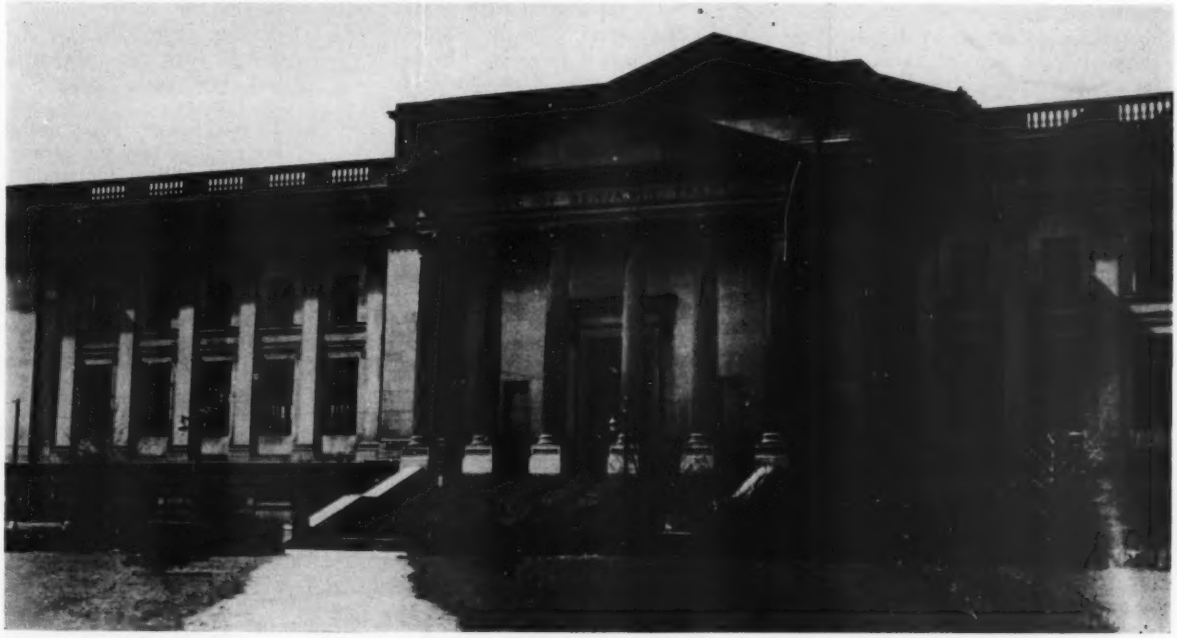

The Air Pollution Disaster— Prevention Program of Los Angeles County*

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During the past decade there has been a growing public awareness of air pollution in most densely populated urban areas of the nation. The occurrence of air pollution attacks of disaster proportions in London, England; Donora, Pennsylvania; Meuse Valley, Belgium; Poza Rica, Mexico; and other places has brought into public focus the potential danger of this newest problem in urban growth.

As in other areas throughout the nation, the air pollution control program of Los Angeles County has been aimed primarily at the elimination of the public nuisance problems generated by smog, such as eye irritation, damage to vegetation, and reduced visibility. Based on inauguration of proper control measures for each significant source of pollution contributing to these nuisance problems, the program is guided by the assumption that the full control of these sources will lead to acceptable reductions in the over-all problem and thereby render all but impossible the occurrence of a public health disaster.

Despite the marked gains scored by rigid control efforts, the tremendous growth of Los Angeles County and the complexity of the air pollution problem result in continued intense and prolonged attacks of smog during the summer season. These have become the normal course of events for more than ten years, and have given birth to public concern over the possible occurrence of serious health disturbances during these periods.

Particularly severe attacks of smog during the fall months of 1953 and 1954 resulted in widespread concern among the general public, lay groups, and medical associations that Los Angeles might be on the brink of a London-type disaster. Although later evidence has failed to substantiate this view, the concern was great enough that the 1954 Grand Jury urged the establishment of an official and formalized disaster-prevention program by the County Air Pollution Control District.

To our knowledge, the program which has developed out of these recommendations is the first to be promulgated in any urban area of the United States.

Development of the Program

The complete development of the program can be represented historically in three phases:

(1) The initial planning phase was one in which advisory committees played the most prominent role. Having accepted in principal the need for some type of emergency program to be enacted in the event of a disaster, the governing board of the APCD (the Los Angeles County Board of Supervisors) appointed a citizens committee in the Fall of 1954 to outline general recommendations for such a program. In the same month, a separate 12-member medical and scientific committee was appointed to establish the contaminant concentration standards which would govern the program. After several months of study and deliberation, these committees produced a recommended program which was enacted into law on June 21, 1955, as Regulation VII of the Air Pollution Control District's Rules and Regulations.

(2) The second phase in the development of the program was one in which the principal objective was the inauguration of a full-scale disaster prevention program as required and outlined by Regulation VII. This phase is represented by the initial administrative efforts of the District to implement the requirements of the newly-enacted regulation.

(3) The third and present phase in the history of this program is one involving operational problems and the refinement and improvement of the original program to better meet its basic objectives in the most effective and efficient manner, with the least possible expenditure of scientific talent and tax dollars.

From its beginning, the disaster-prevention program has had these objectives:

(1) To identify the specific contaminants present in smog which are capable of inducing health disturbances.

(2) To establish concentration standards for these contaminants which provide a *safe margin* in the event of adverse meteorological conditions which would tend to concentrate their dosage in the Los Angeles Basin and to prevent their rapid dispersion and evacuation from populated areas.

(3) To establish means of measuring continuously the presence of these critical contaminants in the Los Angeles atmosphere.

(4) To establish emergency methods which may be implemented in the event measured concentrations approach the standards established as potentially harmful to the public.

The opening preamble of the regulation as enacted in June 1955 stated that *this emergency regulation is designed to prevent the excessive build-up of air contaminants and to avoid any possibility of a catastrophe caused by toxic concentrations of air contaminants. Past history indicates that the possibility of such*

* Presented at the 50th Annual Meeting of the Air Pollution Control Association, held at St. Louis, Mo., June 2-6, 1957.

a catastrophe is extremely remote. The Air Pollution Control Board deems it desirable to have ready an adequate plan to prevent such an occurrence, and in case of the happening of this unforeseen event, to provide for adequate actions to protect the health of the citizens in the Air Pollution Control District.

The regulation spelled out several requirements which were to be a responsibility of the Air Pollution Control Officer. In summary, these requirements were:

(1) That an air sampling network be established, consisting of 14 permanently located stations which would monitor the atmosphere continuously for 4 specific contaminants — ozone, sulfur oxides, nitrogen oxides, and carbon monoxide.

(2) That the Control Officer develop detailed plans calling for the shutdown of significant air pollution sources in the event alert stages were reached for any 1 of the 4 contaminants enumerated in the rule. As enacted, the regulation established 3 alert levels for each of the contaminants.

The first alert level for each contaminant represented a *safe* level, but one approaching the point where preventive action would be required. This alert level was established primarily as a *warning* level.

The second alert level for each contaminant was described as one in which *a health menace exists in a preliminary stage.* The third alert level was judged to be one in which *a dangerous health menace exists.*

Reflecting the best thinking of the medical and scientific members of the original advisory committee, the alert levels established for each contaminant are set forth in Table I.

Succeedingly more stringent controls were specified for each alert level:

During the first alert level the regulation prohibited all refuse burning within the limits of the Los Angeles Basin and required the Control Officer to secure the voluntary cooperation of the public in limiting use of all privately-owned vehicles.

During the second alert level the Control Officer would ask industrial establishments to implement voluntary shutdown plans and, in the event the implementation of these plans failed to halt rising concentrations of contaminants, the Control Officer was authorized, with the advice of a special emergency action committee and with the approval of the Air Pollution Control Board, to inaugurate *such compulsory curtailment activities as he may deem necessary.*

During the third alert level the Air Pollution Control Board would request the Governor to declare a state of emergency and would be authorized to take more vigorous police action as set forth in the California Disaster Act.

Notable in the original regulation was the emphasis on voluntary cooperation. The public was to limit voluntarily the use of privately-owned vehicles, and industry voluntarily was to develop shutdown plans for their plants. The plans would be activated in the event of a second alert. The Control Officer was given the task of prescribing the precise form the shutdown plans would assume and the enormous task of making industry fully aware of the regulation in an effort to stimulate the production of the plans.

At the time the regulation was enacted, Board members publicly stated that, in the event industry failed to assume its responsibilities for the voluntary provisions of the law, the production of shutdown plans would later be made a compulsory provision of the regulation.

(3) The Control Officer was given the further responsibility for declaring the existence of an alert to the public. In the words of the original regulation, *the Air Pollution Control Officer shall declare the appropriate alert whenever the concentration of any air contaminant has been verified to have reached the standards set forth . . .*

. . . The Air Pollution Control Officer shall immediately communicate the declaration of the alert to the Los Angeles County Sheriff's office and that office shall broadcast the declaration of an alert by the Sheriff's teletype and radio system to the Sheriff's substations and the city police departments. The Sheriff's main office and substations shall take whatever steps are necessary to make known the declaration of the alert to recognized mass media of communication. Thereafter all persons in the APCD shall be presumed to have notice of the declaration of the alert.

During the first alert level, the Control Officer was further directed to make use *of all appropriate mass media of communication* in the interest of requesting the public *to stop all non-essential use of vehicles in the Basin and to operate all privately-owned vehicles on a pool basis, and . . . request all employers to activate employees' car pools.*

Perhaps the most difficult communication job assigned to the Control Officer was that of communicating knowledge of alerts to industrial establishments so that shutdown plans might be activated.

(4) A full-scale public information and education program also was required by the program. Again, in the words of the regulation, *the Air Pollution Control Officer shall inform the public of ways in which air pollution can be reduced and shall request voluntary*

TABLE I
Alert Stages For Toxic Air Contaminants (in ppm.)

	1st Alert	2nd Alert	3rd Alert
Carbon monoxide	100	200	300
Nitrogen oxides	3	5	10
Sulfur oxides	3	5	10
Ozone	0.5	1.0	1.5

cooperation from all persons in all activities which contribute to air pollution. Civic groups shall be encouraged to undertake campaigns of education and voluntary air pollution reduction in their respective communities. Public officials shall be urged to take promptly such steps as may be helpful to reduce air contamination to a minimum within the areas of their authority. Employers shall be requested to establish car pools which can be activated promptly if necessary. Users of automotive vehicles shall be urged to keep motors in good condition and to plan routes and schedules which will contribute minimum contamination to critical areas of pollution.

The regulation further stated that *all industrial, commercial and business establishments which emit hydrocarbons or . . . (the air contaminants selected as triggers for the declaration of alerts) should critically study their operations from the standpoint of air contamination and should take appropriate action voluntarily to reduce air pollution.*

(5) The final responsibility assigned to the Control Officer involves the continuing revision, adjustment, and improvement of the disaster-prevention program. To assist the Control Officer in this respect, a 15-member scientific committee was activated under the regulation.

Composed of medical and air pollution experts, this committee was entrusted with responsibility for studying and recommending to the Control Officer the most *suitable methods for measurement of air pollutants* and for recommending any changes in the alert standards.

The regulation established the committee as a permanent and continuing group, and stated that *the scientific committee shall serve in a consultant advisory capacity to the Control Officer concerning any air pollution health problem which may arise. The scientific committee shall also advise the Air Pollution Control Board on any recommended changes in this emergency regulation which will provide greater protection of the health and welfare of all persons within the Air Pollution Control District.*

In summary, the initial disaster-prevention regulation created a formal organization in which the Control Officer would serve as Chief Executive and in which he would be assisted by 2 official committees:

(1) A scientific committee which would be concerned with a continuing study of the emergency program and with the development of recommendations for revisions in the alert standards.

(2) An emergency action committee which would advise the Control Officer and the Control Board as to specific steps which should be taken in the event a second alert level were reached — a level described as one in which a preliminary health hazard exists.

An enormous task confronted the District: The establishment of a 14-station air monitoring program, the solicitation of voluntary shutdown plans from private industrial establishments, the establishment of mass communication procedures, the development of a master compulsory shutdown plan susceptible of implementation during the final steps of a second alert, and the sponsorship of an information program designed to acquaint the public with ways in which they could limit the output of pollutants during any alert level.

The Air Monitoring Program

The key element in the entire program, without which there could be no effective community disaster-prevention measures, is the air monitoring program. This has also proven to be the most expensive and time-consuming element in the entire program.

Based on studies performed by medical and scientific members of the advisory committees, the regulation required the construction of a 14-station air monitoring network with each station providing almost continuous measurements of sulfur dioxide, nitrogen oxides, carbon monoxide, and ozone. Selection of the contaminants to be used as indices for the declaration of alerts, and the designation of concentration values necessary for individual contaminants to trigger alerts, is specified by the regulation to be a responsibility of the Scientific Committee[1]. Monitoring methods are developed by the District staff with the advice, counsel, and approval of the Scientific Committee.

No pretense is made that the alert standards, the monitoring system or methods inaugurated by Regulation VII are concerned with the measurement of smog, per se. The eye-smarting, plant-damaging and visibility-reducing phenomenon called smog in Los Angeles has not yet been demonstrated to be a hazard to public health, according to the California State Department of Public Health[2], nor is there yet a single, immediate, and objective method by which its intensity may be determined.

The single criterion upon which the program is based is the capacity of individual contaminants to cause health disturbances. The program is not and, under the law, apparently cannot be, established to protect the public's comfort or discomfort. The unusual powers afforded the District by Regulation VII virtually could halt the entire economy of Los Angeles County during second and third alert levels. In view of this potential power to deprive the use of private property, the common law and constitutional safeguards dictate that the program must be based solely on factors affecting the public's health and safety.

In view of this consideration, the Scientific Committee selected the 4 alert contaminants on the basis of their individual toxicity. Each is found in comparatively heavy concentrations in the Los Angeles atmosphere, and each is known to be toxic at certain concentration levels.

In view of the potential importance of the program to the community, alert standards were recommended by the Scientific Committee which recognized a comfortable margin of safety between known levels of toxicity and those established as standards for the declaration of alerts. The enactment of these recommendations into law has resulted in the declaration of 25 first alerts based on ozone readings, 15 of which occurred during 1955 and 10 during 1956. No second or third alert values have been reached, nor have any first alert values been reached for any contaminant other than ozone. (Table II)

Although the regulation prescribed the construction of a 14-station air monitoring network, upon its enact-

TABLE II

Resume of Alert Data — Alerts Called Under Regulation VII
(July 1955 - May 1957)

Date	Station No. & Location	Ozone Readings (peak value)	Time of Peak Value	Time Above Alert Level	Alert Stage	Duration of Alert
7-18-55	1 Downtown	0.53 ppm.	11:30 - 11:41	0 hr. 11 min.	——	not called
8- 1-55	4 Pasadena	.57	12:00 - 12:10	10	First	0 hr. 35 min.
8-26-55	15 Vernon	.64	11:05	41	First	2 19
8-27-55	4 Pasadena	.58	1:16	57	First	1 35
8-29-55	4 Pasadena	.60	11:30	2	First	1 18
8-30-55	15 Vernon	.52	12:07 - 12:17	10	First	1 8
9- 1-55	15 Vernon	.60	2:18	4	——	not called
9- 6-55	15 Vernon	.56	11:15	2 0	First	3 6
9-12-55	15 Vernon	.50	10:44	3	——	not called
9-13-55	1 Downtown	.85	11:18 - 11:37	2 19	First	3 9
	15 Vernon	.90	11:46 - 12:16	2 28		
9-14-55	1 Downtown	.64	10:52 & 11:12	37	First	2 40
9-20-55	1 Downtown	.54	11:46 - 12:06	1 32	First	1 48
	15 Vernon	.50	11:43	3		
9-30-55	4 Pasadena	.65	12:28	26	First	1 20
10- 1-55	4 Pasadena	.63	12:05	17	First	51
10- 7-55	1 Downtown	0.55	10:27 - 10:31 & 11:27	1 0	First	1 19
10-29-55	15 Vernon	.63	2:38	1 20	First	2 44
11- 3-55	1 Downtown	.53	11:28	3	First	1 35
	15 Vernon	.57	12:17	1 7		
11- 4-55	15 Vernon	.51	11:42 - 11:46	4	——	not called
11- 6-55	2 West L.A.	0.50	11:18	3	——	not called
11-28-55	4 Pasadena	.52	12:28 - 12:32	4	First	25
6-11-56	15 Vernon	.70	10:23	1 58	First	2 27
6-12-56	15 Vernon	.70	9:51 - 10:12	45	First	1 22
7- 6-56	1 Downtown	.60	11:25	25	First	1 50
8-22-56	5 Rivera	.60	10:50 - 11:06	31	First	2 32
	6 Basset	.60	11:50 - 12:19	39		
8-23-56	6 Basset	.60	12:51	1 33	First	2 33
	7 Azusa	0.60	2:29	44		
	9 Burbank	.50	1:42 - 2:29	27		
9-18-56	7 Azusa	.50	12:30 - 12:43	13	First	0 52
	9 Burbank	.50	12:24 - 12:31	7		
9-24-56	1 Downtown	.50	10:51 - 11:11	20	First	35
9-26-56	1 Downtown	.55	9:30 - 10:35	1 48	First	2 53
	15 Vernon	.50	10:43 - 10:51	8		
9-27-56	15 Vernon	.55	11:29 - 11:39 & 11:54	1 9	First	1 15
9-28-56	1 Downtown	.55	10:10	53	First	3 35
	15 Vernon	0.70	10:36 - 10:39	2 36		

ment there remained the task of selecting the specific sites for the stations, and of determining the monitoring methods which could, with the approval of the Scientific Committee, be employed in the system.

Based on data from 76 meteorological stations, wind flow patterns throughout the Basin were analyzed

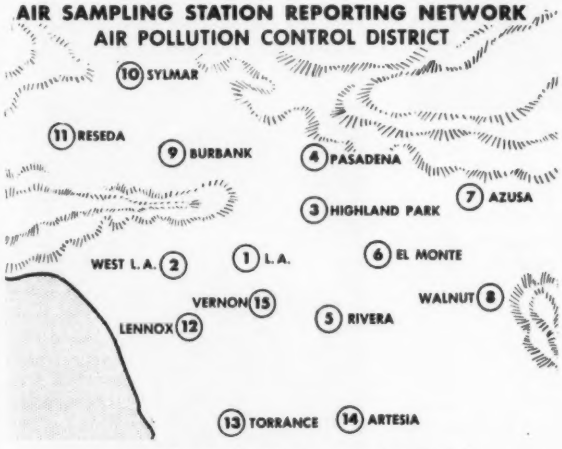
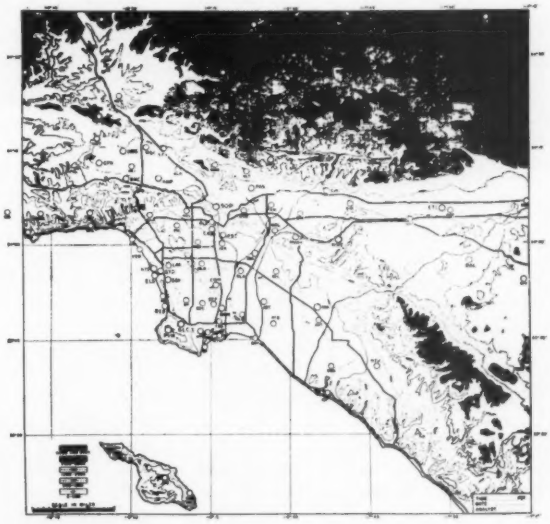


Fig. 1. (above) Map of air monitoring network.

Fig. 2 (right) Map of APCD weather station network.



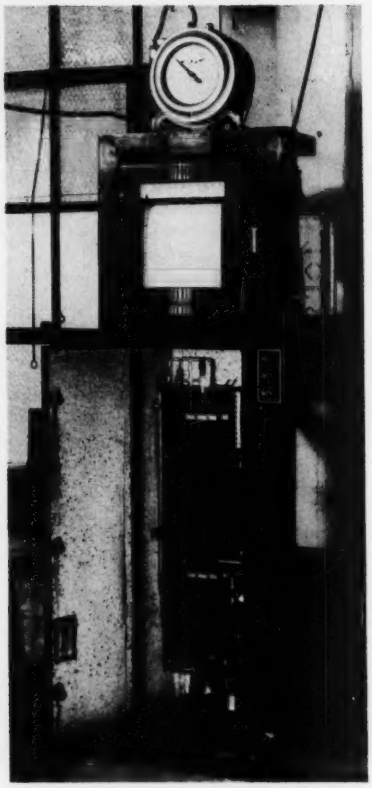


Fig. 3. A Thomas Autometer, an automatic instrument included in each sampling station for the mandatory measurement of sulfur dioxide.

to determine those locations at which contaminant concentrations would be most representative of general conditions throughout the Basin. When completed, these studies indicated a need for site locations radiating outward from the center of Los Angeles, with at least one station in each major geographic area of the County. (Fig. 1 and 2).

Since only 3 sampling stations were in operation for research purposes at the time the regulation was enacted, steps were taken to expand the network to the required number.

During the period when the network was being planned, the instrument specifications prepared, and the constructed units inspected, calibrated and installed, a minimum of 15 technicians were required for this single element in the total program. At the present time, the Air Monitoring Section of the District contains 45 employees with an annual payroll in excess of $225,000.

Excluding the cost of additional monitoring instruments installed in each station to meet research purposes, the establishment of an air monitoring network to meet the specifications established by Regulation VII has required a capital investment of approximately $18,000 per station. The complete costs of planning, installing, and placing in operating condition the entire network approach $400,000. The operation and maintenance of the total air monitoring network, both to meet the requirements of Regulation VII and for research purposes, will require an expenditure of approximately $400,000 during the twelve month period beginning July 1, 1957. (Fig. 3, 4, 5, 6, 7, 8 and 9)

Since values recorded on monitoring instruments are not transmitted to the central control center by automatic methods, all stations must be manned on days when heavy smog concentrations are expected. Smog forecasts developed daily by the District's meteorologists have been revised so as to provide more specific advance information as to the probable occurrence of alerts or heavy smog concentrations. This information guides decisions as to whether all stations will be manned on any given day. During these heavy smog episodes, values recorded on the instruments are read by field enforcement or laboratory personnel and telephoned to a central alert center for posting.

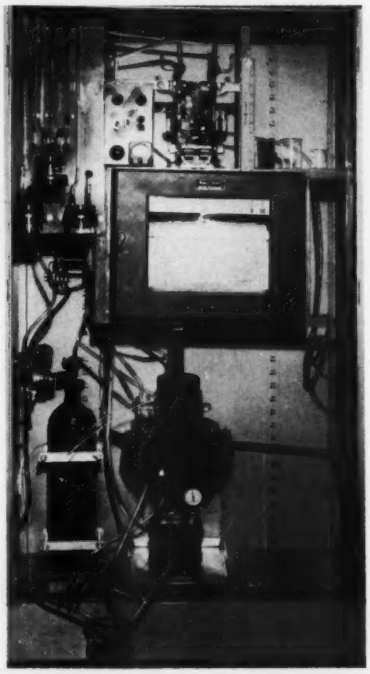


Fig. 4. Automatic recording device used for measurement of nitrogen dioxide and nitric oxide.

The equipment and procedures currently employed in the air monitoring program in compliance with Regulation VII, include the following:[3]

(1) Carbon Monoxide — Concentration of this contaminant is measured automatically and continuously by means of the Mine Safety Appliance Company's Lira Gas Analyzer (non-dispersive, differential, infrared analyzer).[4]

(2) Nitrogen Oxides — Sampling for this contaminant is automatic and continuous, and is based primarily on the colorimetric determination of nitrogen dioxide using the Saltzman modification of the Griess-Ilosvay procedure.[5]

(3) Ozone — This contaminant is measured manually by the rubber cracking method of Bradley and Haagen-Smit. The air to be sampled is drawn at a rate of 1.5 l./min. through a glass tube across a bent rubber strip. A reaction between ozone and rubber causes cracking or serration of the exposed cut edges of the rubber strip at the point of greatest strain or tension (at the top of the loop) at a rate proportional with the ozone concentration, the flow rate, and the diam.

Fig. 5. The Mine Safety Appliance Company's Lira Gas Analyzer used for automatic and continuous measurement of carbon monoxide.

Fig. 6. APCD Air Sampling Station in Pershing Square, located in Downtown Los Angeles. Station was designed to blend with park environment in the area.

of the glass tube in which the rubber strip is exposed. By means of this relationship, the time necessary to cause initial cracking of the rubber strip can be translated into ozone concentration in ppm. by volume.

(4) Sulfur Dioxide — Sampling for this contaminant is carried out automatically and continuously by means of the Thomas Autometer.[6]

In addition to monitoring the atmosphere for the 4 contaminants listed in Regulation VII, the APCD samples for hydrocarbons, aldehydes, total oxidant, particulate matter, and oxidant precursor. (Fig. 10, 11, 12, 13, 14, 15, 16, 17 and 18).

Experience with the program has indicated that, even during particularly intense smog attacks, maximum concentration values for the 4 trigger contaminants endure only briefly. Of the 25 alerts declared to date, in only 13 instances did ozone values higher than 0.5 ppm. occur for more than 30 min. No alerts have yet been declared for contaminants other than ozone. The maximum values ever recorded in Los Angeles County for the 4 contaminants are shown in Table III.

Since the toxicity of each of these contaminants is a function of both concentration and time of duration, the Scientific Committee has given serious consideration to revision of the standards so as to take into account the factor of time of duration which is not now recognized by the regulation. The probable effect of such a revision would be to lessen rather than to increase the number of alerts which would be called.

Declaration of Alerts

Having established the air monitoring network, the task remained of establishing an effective communication network for the declaration of smog alerts.

In the early period of the program's history, the tools of communication were primitive and unwieldy, but, nevertheless, remarkably effective.

With field personnel reading the monitoring instruments, the values were telephoned to a private phone in the control center where they were received by a technician assigned to the data reduction section. Here, the values were recorded and announced periodically to the Director of Enforcement, who serves as Alert Administrator, and to the Public Information Officer and other staff members concerned with the administration of the program.

Fig. 7. Exterior view of air sampling facility in Pasadena.

Whenever ozone values exceeded 0.35 ppm., incoming calls were routed immediately to the Alert Administrator.

When an alert-level value was recorded in the field, an immediate check was made to determine its accuracy, and the report was then phoned directly to the Alert Administrator for the declaration of the alert.

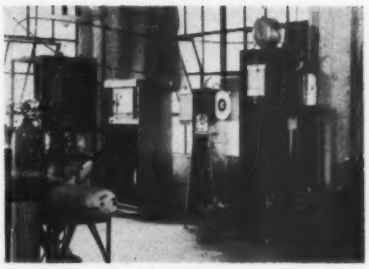


Fig. 8. Interior view of a typical air sampling station required by Regulation VII. Pictured (from left to right) are: Carbon Monoxide Recorder, Total Oxidant Recorder, Chaney Auto Sampler, Thomas Autometer for Sulfur Dioxide. Stations are manned during heavy smog episodes assuring prompt transmittal of instrument readings to Central Control Center.

The declaration was made by the Administrator through telephoning the Sheriff's teletype center, the Los Angeles City Police Department radio center, the District's Public Information Officer, and the radio dispatch center of the Air Pollution Control District.

At the Sheriff's office, a teletype was immediately dispatched to all local public safety organizations.

The Los Angeles City Police Department carried the announcement on its radio band, which is monitored by most radio stations through an automatic recording instrument known as Sigalert. This instrument records all bulletins designated for Sigalert by the police dispatcher, and, at the time of recording, displays a visible light and sounds an alarm which may be heard by personnel of the radio station. Prior agreements with the Southern California Radio Broadcasters Association resulted in use of the Sigalert announcement over most public radio and television facilities.

In the District's public information office, notification of an alert prompt-

Fig. 9. Pictured is apparatus used in the manual sampling of ozone. All monitoring stations are manned during anticipated heavy smog episodes to permit manual sampling.

TABLE III
Maximum Concentrations of Toxic Contaminants

Contaminant	Concentration, in ppm.	Date	Location
Carbon Monoxide	83	9-26-56	Central Los Angeles
Nitrogen Dioxide	1.74	9-17-53	Central Los Angeles
Ozone	0.90	9-13-55	Vernon
Sulfur Dioxide	1.70	5-18-55	El Segundo

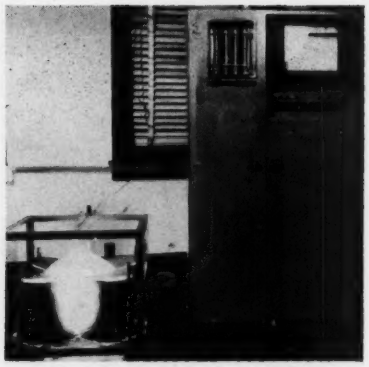


Fig. 10. Automatic Oxidant and Oxidant Precursor Recorder included in APCD air monitoring network. Device captures samples of night air and, by irradiation, determines potential oxidant content as it will occur the following morning.

ed several dozen telephone calls to the mass media, official agencies, and industries. Notification of the alert was made first to the news wire services. In Los Angeles these include the Associated Press, United Press, and City News Service. Prior arrangements with these groups assured that the message would be transmitted to all subscribers. Further telephone calls were then made to radio and television stations, to the offices of the Air Pollution Control Board, and to other official agencies, such as the Weed Abatement Bureaus of the City and County, and the Public Works agencies.

At the District's radio dispatch center, the alert notification was dispatched to all field enforcement units of the District, totalling 135 in number.

From start to finish, this notification process required only 15 min.

Messages carried through this communication network indicated that an alert had been called, indicated the

Fig. 13. Midget Impinger Train and pump utilized for collection of aldehyde samples.

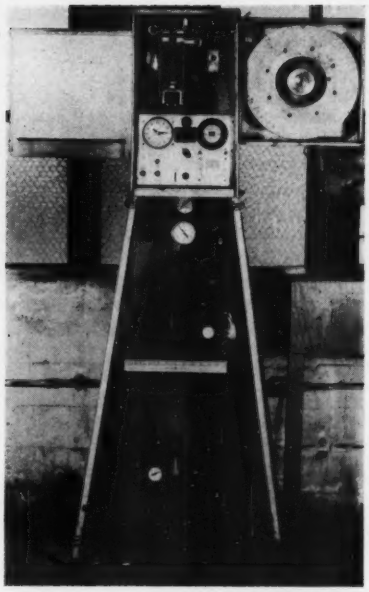


Fig. 11. Chaney Auto Sampler, a continuous and automatic device for measurement of particulate matter.

location and time of the alert value, notified the public to discontinue all refuse burning and asked their cooperation in curtailing use of motor vehicles.

Lists of telephone numbers were maintained in the public information office for plant managers in local industries which might be requested to curtail operations during second alerts. By a prearranged plan, if such an alert had been declared, employees from other offices of the District would be detailed to make the necessary calls. Field enforcement personnel and law enforcement agencies were provided with location lists of large commercial incinerators, whose use is prohibited during first alerts, and of industrial plants which might be subject to shutdown during second or third alerts.

Early experience demonstrated that this communication system possessed several inherent weaknesses:

(1) It was ponderous and unwieldy to such a degree that great latitude for human error was possible.

(2) The procedure for notifying industrial establishments in event of a second alert was believed unworkable — both in view of the time required, and the necessity to reach responsible management officials with concise, and obviously official instructions.

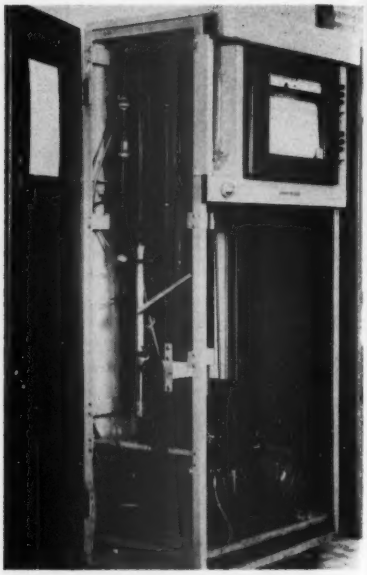


Fig. 12. Oxidant Recorder utilized in measurement of total oxidant concentrations.

Several refinements and improvements, therefore, have been introduced either by amendment to Regulation VII or by administrative directive:

(1) Transmittal of alert values from the District's control center to the Alert Administrator is now accomplished by Telautograph, a device which transmits almost instantaneously a photocopy of messages written on the sending device.

(2) Teletype machines have been installed to link the office of the Alert Administrator with the Sheriff's office, the Los Angeles Police Department, and the major news wire services.

Fig. 14. Apparatus for collection of hydrocarbon samples.

Under present operations, reliance is placed on the Police Department's Sigalert system and on the news wire services for transmittal of the declaration to the organized mass media.

(3) To communicate alert information to local industrial plants, a selective radio-calling facility has been installed in the District's radio dispatch center. The provisions of Regulation VII require key categories of industry to purchase, install and maintain radio receivers capable of receiving alert messages from the Control Officer. The radio receiving unit is designed for operation on a carrier frequency of 39.98 megacycles. The transmitting frequencies selected are such as to preserve a closed communication system to the alert notification process. Governmental officers and agencies playing a role in the overall program are included in the radio system. The receivers installed by each plant cost between $250 and $300 each.

Voluntary Provisions of the Program

To assure that the employment of the monitoring and communication systems would yield desired results, the Regulation and judgment dictated an intensive public education program. Its major purposes were:

(1) To acquaint the general public with preventive measures that might be taken to deter the occurrence of alerts.

(2) To acquaint the general public and industry with the mandatory and voluntary actions required by the program.

(3) To stimulate the preparation of voluntary shutdown plans by local industry and the development of voluntary plant air pollution control programs that might further increase the effectiveness of legally-required control measures not a part of the Disaster-Prevention Program.

Two informational publications entitled, *How You Can Help Fight Smog*, and *How Industry Can Help Fight Smog* were prepared, published and distributed. More than 500,000 copies of these publications have been distributed to date.

Special publications on the Disaster-Prevention Program were prepared and distributed to plant managers in *Information Kits*. The kits contained suggested shutdown plans and guides for the development of plant share-the-ride and plant air pollution control programs. Two Field Representatives were employed by the Air Pollution Control District and given the sole responsibility of meeting with trade and industrial associations and with managers of the larger industries. Their objective was to assist and stimulate plant management in the development of shutdown plans, the inauguration of share-the-ride programs, and the implementation of plant air pollution control programs.

Radio spot announcements were mailed twice monthly to all radio and television stations carrying informational messages regarding the entire program.

In 1956, a coordinated, community-wide share-the-ride program was launched in cooperation with the Los Angeles Chamber of Commerce. Share-the-ride coordinators were appointed in several hundred of the largest plants and commercial establishments, a recommended in-plant ride-sharing program was prepared and distributed, while newsletters and regular meetings provided tips to plant coordinators on the administration of their own programs. Feature articles, cartoons, and radio-TV spot announcements were distributed by the hundreds.

Perhaps the most notorious element in the entire public education phase of the program, was the now famous *Smog Red-Smog Green* system.

Since smog forecasts had long been a public service activity of the Air Pollution Control District, these were turned to use in the voluntary program.

Whenever forecasts indicated the possible occurrence of smog, a *Smog Red* warning was forecast the evening before over radio, television, and on the front pages of the daily newspapers. Through continuing release of radio and television spot announcements the public was informed of the preventives which should be applied during Smog Red Days, such as *No Refuse Burning, Share-A-Ride Today*, and other similar messages. Together with the forecast, the newspapers printed Smog-Red cartoons based on matrixes prepared and distributed by the APCD. These cartoons indicated also the preventive measures which should be taken.

Fig. 15. View of apparatus employed by APCD for automatic collection of nitrogen oxides samples.

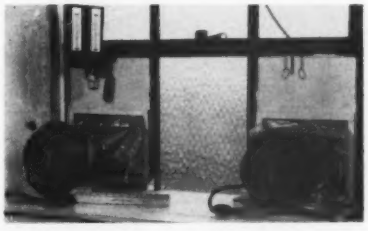


Fig. 16. Staplex Hi-Volume Filter Samplers for collection of ether-soluble aerosols.

Fig. 17. View of equipment used in extraction of ether-soluble aerosol material from filters.

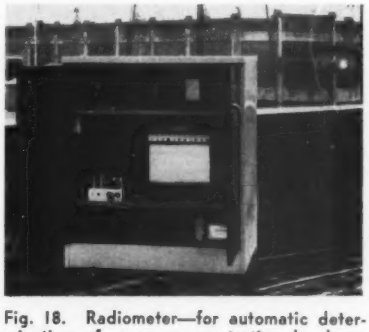


Fig. 18. Radiometer—for automatic determination of ozone concentration by long-path ultraviolet radiation. (Note light source at right of recorder.) This device is being considered as replacement for manual ozone sampling in APCD air monitoring network.

AIR POLLUTION CONTROL DISTRICT — COUNTY OF LOS ANGELES
434 S. San Pedro Street, Los Angeles. MAdison 94711.
PLANT SHUTDOWN PLANS & INFORMATION — REGULATION VII

CODE

Company Name Address Phone Number

	Equipment		Operating data					Shutdown time in minutes		Remarks	For office use only
	Basic	Air pollution control	Process	Products	Hours of day	Days of week	Production and/or consumption	Minimum	Recommended		
1	Extrusion Polishing Lathe	Bag Type Dust Separator	Polishing Aluminum	Aluminum extrusions	8	5		5	5		
1	Caustic Etch Unit Roto-clone	Air Scrubber	Etching Inspection samples				200#/Aluminum etched/day	5	5		
5	Ingot Reheat furnaces — (Recirculating)	None	Heating ingots	Aluminum extrusions	24	5	Approx. 2500 c.f.h. gas consumption	10	30	Hot air circulating fans. Must run until oven temperature drops to 400° F.	
6	Die Preheating furnaces	None	Heating dies	Steel dies	24	5	Estimated 800 c.f.h. gas consumption	5	5		
4	Aging Oven	None	heat-treating Al. extrusions	Aluminum extrusions	24	5	Approx. 4500 c.f.h. gas consumption per oven	10	30	Hot air circulating fans. Must run until oven temperature drops to 400° F.	
8	Rotoclone units on presses	Air Scrubber	Removing caustic fumes	Aluminum extrusions	24	5	Will handle up to 2500 c.f.m. exhaust air	5	5		
1	Rotoclone on caustic tank of die cleaning unit	Air Scrubber	Remove caustic fumes	Clean steel dies	24	5	Will handle approx. 1000 c.f.m.	5	5		
1	Oven for die repair	None	Heating dies	Repaired steel dies	24	5	Approx. 800 c.f.h. gas consumption	5	5		

	Day Shift	Swing Shift	Night Shift
Number of office and administrative personnel	65	11	3
Number of all other personnel	166	108	48
Number of motor vehicles used daily by office and administrative personnel from home to work	52	9	3
Number of motor vehicles used daily by all other personnel	133	95	38
Number of company owned motor vehicles used daily	3	2	1

Signature
Responsible Official
Print or Type Name
Title
Date October 17, 1956

16-60 D 67

Fig. 19. Typical plant shut-down plan.

On any day when no smog was forecast, a Smog Green announcement was flashed, and this proved to be the downfall of the entire system.

The terms *RED* and *GREEN* had been devised to attract public attention and to convey a simple understanding of the actions which would be necessary. The term *RED*, like the typical stop-light, meant *STOP ALL UNNECESSARY AIR POLLUTING ACTIVITIES.* The term *GREEN* was simply the go-ahead signal for all normal activities. However, when people throughout the nation heard of the terms, reports filtered back to the Los Angeles City Council and to local business groups that these outlanders and potential tourists imagined that Los Angeles had smog every day — some days green, and other days red. On request, these terms were dropped, but the smog forecasts and all other elements of the system continued.

Shut Down Plans

Critical to the success of the entire disaster-prevention program is the plan for curtailment of air polluting activities during alert periods. As originally enacted, Regulation VII envisioned the submittal of voluntary shut-down plans from industries contributing significant contaminants to the atmosphere, and the development of a *master plan* by the APCD. The *master plan* would detail the over-all curtailment and control steps which would be activated during a second or third alert level.

Under the regulation, the advent of a second or third alert level would result in the inauguration of an industrial shut-down procedure capable of coping with the immediate crisis. All shut-down orders would be issued under the authority of the Air Pollution Control Board acting with the advice and counsel of the Emergency Action Committee and the Air Pollution Control Officer. As Chief executive officer of the program, the Control Officer would provide such detailed information to the Board and the Committee as is necessary to the issuance of sound and effective shut-down orders.

To meet the problems posed by any second or third alert level, informa-

tion required would include complete data as to the types of contaminants emitted from individual industrial processes, the amounts of contaminants emitted/unit of time, the time required for partial and complete shutdown of the process, and other such vital data. It is apparent that the assembly of such information by the Control Officer and the development of a recommended *master plan* would be impossible without individual shutdown-plant plans containing specific information which could be studied, consolidated, and incorporated into an overall plan of action.

However, by July 25, 1956—more than 1 year after the enactment of Regulation VII—only 50 voluntary shutdown plans had been received from the more than 15,000 industrial plants within Los Angeles County.

This comparatively insignificant response followed more than 1,000 telephone calls and almost as many personal contacts by members of the District with the industries affected. The policy of awaiting the voluntary submission of shutdown plans resulted in only 9 plans which outlined a detailed workable program. The remainder of the total of 50 plans received were either vaguely descriptive of a general program or more often merely a pledge of cooperation and a plan for the establishment of car pools.

Since the Air Pollution Control Officer had no legal authority under the Regulation, either to compel the submittal of shutdown plans or to approve or reject such plans, it was necessary to modify this portion of the existing Regulation making it mandatory that such curtailment or shutdown plans be submitted to the Air Pollution Control Officer after written notice to the operators of an industry, business, commercial establishment, or activity. Consequently, on July 26, 1956, the regulation was revised so as to make mandatory the submittal of shutdown plans by industry.

As revised, the regulation states: *If the Air Pollution Control Officer finds that any industrial, business, or commercial establishment or activity emits hydrocarbons or any of the contaminants named in Rule 156,[7] he may give written notice to the owner or operator of such industrial, business, or commercial establishment or activity to submit to the Air Pollution Control Officer plans for immediate shutdown or curtailment, in the event of an air pollution emergency.*

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SIZE DISTRIBUTION
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Acting under the authority of the revised regulation, shutdown plans were requested from individual plants representing more than 10 categories of industrial operations within Los Angeles County.

Shutdown plans were requested from every person who owned, operated, maintained or used any:

(a) Petroleum refinery.
(b) Chemical processing plant, except a plant engaged exclusively in packaging, mixing or blending less than 1,000 lb./hr.
(c) Open hearth steel furnace.
(d) Secondary non-ferrous refinery.
(e) Electric arc furnace.
(f) Asphalt saturator.
(g) Asphalt paving plant.
(h) Ferrous foundry.
(i) Non-ferrous foundry in which metals other than aluminum, zinc, lead or alloys in which aluminum, zinc, or lead is the principal ingredient are processed except a foundry in which the throughput does not exceed 100 lb./hr.
(j) Plant manufacturing paint or varnish.

Following receipt of the shutdown plans from plants in these categories, a comprehensive study and evaluation was undertaken of the data submitted. This was a considerable task because of the large number of companies involved, the diversity of their activities and the extremely complex nature of many of the operations. A number of plans received were found incomplete or unacceptable for some reason and necessitated conferences with the persons involved and the resubmittal of revised plans. (Fig. 19).

The first step taken in the evaluation of the shutdown plans was the compilation and tabulation by companies and categories of industries or activities, of all of the data submitted including car pool data and both *minimum* and *recommended* shutdown times. By making a comparison of the tabulated data for a particular category of industry or activity, it was possible to evaluate shutdown times for similar operations or units of equipment. Where shutdown time appeared excessive or did not correspond with the average time observed from the survey, the companies were contacted and the reasons for such deviations from the norm were determined.

Regulation VII states: *It shall be the objective of such program to result in bringing about a diminution of air contaminants which occasioned the Second Alert and to prevent any increase thereof in order to protect the health of all persons within the area affected by the alert. It shall also be the objective of such plans that they may be effective to curtail the operations of industrial, business, commercial, and other activities within the basin, but without undue interference with the operations of public utilities or other productive, industrial, business, and other activities, the conduct of which is essential to the health and welfare of the community. It is further intended that any said plan of action shall not jeopardize the welfare of the public or result in irreparable injury to any means of production or distribution or the rendering of public utility services.*

In view of this, it was determined that to effect a shutdown or a curtailment of industry by employing the *minimum* shutdown time would constitute *such drastic remedial measures as to completely disrupt the economic life of the community or to result in irreparable injury to any form of production, manufacture, or business* which would be contrary to the provisions of the Regulation. Consequently, under the *Master Plan* of action it is anticipated that when a Second Alert occurs industry shutdown plans will be carried out in accordance with the *recommended time* stipulated.

In many cases, in the shutdown plans submitted, the *recommended time* and the *minimum* time are the same. It is anticipated that in the event of a third alert a crash program could be effected calling for the promulgation of shutdown plans on a *minimum* time basis.

After all of the shutdown plans submitted to the District had been reviewed and approved as meeting the requirements of the law, the companies and the persons submitting such plans were notified by registered mail of the reecipt and approval of their plans. They were further notified that in the event of an air pollution emergency alert, they would be directed by the Air Pollution Control Officer to execute the curtailment or shutdown provisions of their plans in accordance with Regulation VII.

The original list of plants from whom shutdown plans were requested under the terms of the revised regulation is now being expanded. During the compilation of the original list, it was recognized that the list represented merely a starting point and that not all the businesses, commercial and industrial establishments capable of emitting hydrocarbons or any of the *alert* contaminants were included. In the expanded program it is proposed that the regulation be revised and amended so as to include the following categories of industrial or commercial operations:

(a) Petroleum refineries.

(b) Bulk gasoline loading facilities for tank vehicles, tank cars, or marine vessels from which facilities 20,000 gallons or more of gasoline are loaded/day. For purposes of this paragraph, gasoline means any petroleum distillate having a Reid vapor pressure of 4 lb. or greater, and facilities means all gasoline loading equipment which is both (1) possessed by one person, and (2) located upon a single parcel of land or upon contiguous parcels of land.

(c) Asphalt saturators.

(d) Asphalt paving manufacturing plants.

(e) Asphalt manufacturing plants.

(f) Chemical plants which (1) react or produce any organic liquids or gases, (2) produce sulfuric acid, nitric acid, or phosphoric acid or sulfur.

(g) Paint, lacquer, or varnish manufacturing plants in which 10,000 gallons or more/month of solvents, diluents, or thinner, or any combination thereof, are combined or manufactured into paint, enamel, lacquer, or varnish.

(h) Rubber tire manufacturing or rubber reclaiming plants.

(i) Automobile assembly or automobile body plants.

(j) Metal melting, refining, or smelting plants in which a total of 2,500 lb. or more metal is in a molten state at any one time or is poured in any 1 hr.

(k) Rock wool manufacturing plants.

(l) Glass or frit manufacturing plant in which a total of 4,000 lb. or more glass or frit or both is in a molten state at any one time or is poured in any 1 hr.

It is to be noted that the proposed list includes six additional general classifications of industry: gasoline loading and handling facilities, asphalt manufacturing plants, rubber tire manufacturing or rubber reclaiming plants, automobile assembly or automobile body plants, rock wool manufacturing plants, glass or frit manufacturing plants.

It is contemplated that, as soon as time and personnel permits, the subject of combustion sources, solvent sources, as well as other miscellaneous sources, will be thoroughly investigated and a decision made as to which ones shall be requested to submit shutdown plans.

To assure the constant timeliness of the master shutdown plan and of individual plant shutdown plans, certain procedures have been evolved. Under these procedures, applications from industrial or commercial concerns for the construction and operation of equipment capable of emitting air contaminants[8] are brought to the attention of the District's Evaluation and Planning Staff, the organization responsible for the maintenance of the master plan. Upon receipt of this notification by the Evaluation and Planning Staff, the appropriate request for shutdown plans is mailed to the company involved.

Periodic physical inspections of each plant in the County also are performed by the Enforcement Division to assure that individual plant shutdown plans contain accurate and current information. Under the present program, it is contemplated that physical inspections of plants affected by Regulation VII will be performed at least once every 6 months. Duplicate copies of individual plant shutdown plans are maintained by the Enforcement Division to serve as a basis for this inspection program.

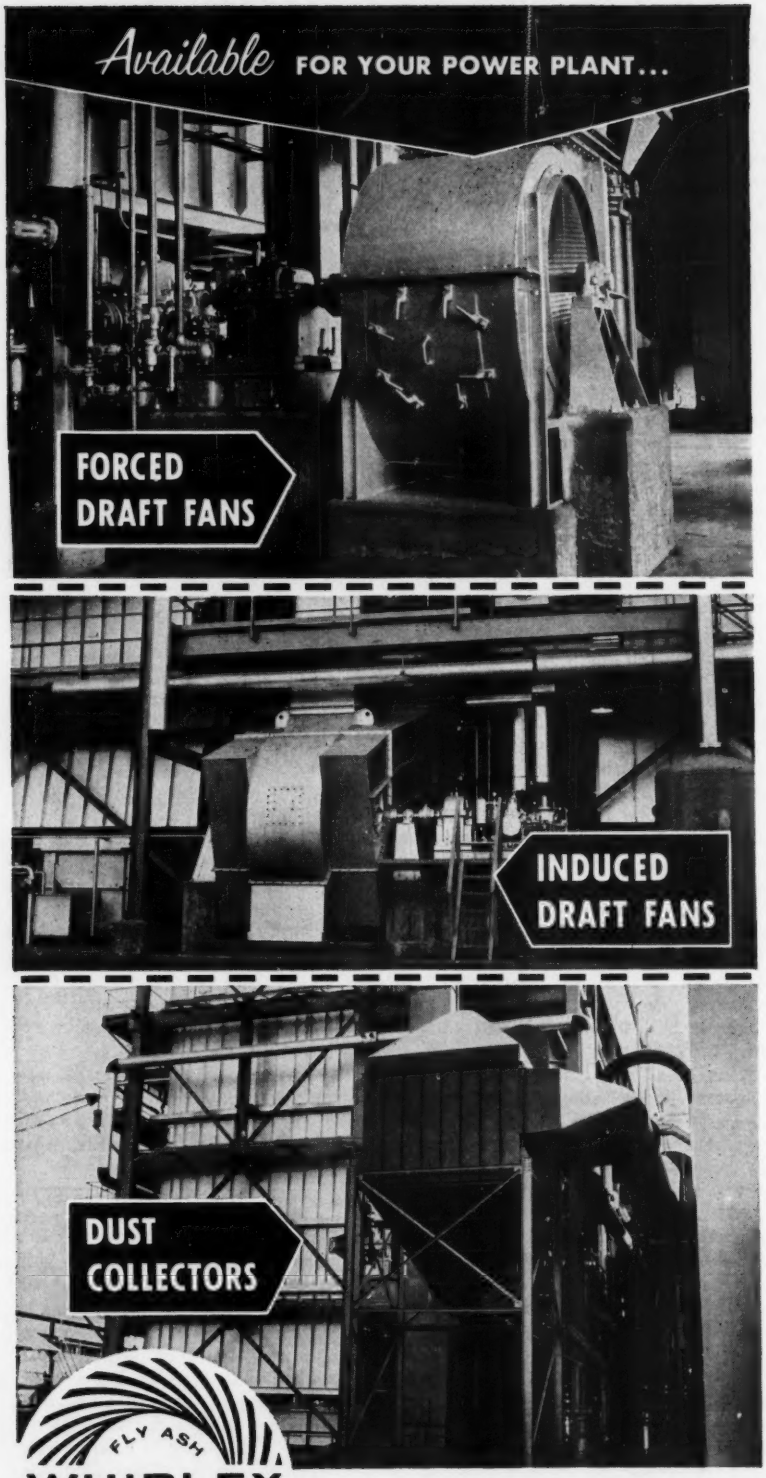
Conclusions and Summary

It is recognized that the formalized disaster-prevention program of Los Angeles falls far short of perfection and that continued improvements and refinements will be necessary to assure the full accomplishment of its basic objective: the prevention of health-disturbing episodes of air pollution.

Several problems have evidenced themselves during the administration of the program since its inception nearly 2 years ago.

(1) The inauguration of compulsory shut-down programs is impossible until second or third alert contaminant concentrations are reached. This raises the obvious question as to whether or not we're locking the barn door after the horse has been stolen. Research has demonstrated that once organic materials and oxidants enter the atmosphere, little can be done to prevent the occurrence of smog-forming oxidation processes in the presence of sunlight. One of the products of these reactions is ozone — the contaminant upon which all alerts have been declared during the two-year history of the program. In this sense, at least, it would appear more effective to curtail activities contributing to the formation of ozone substantially in advance of the occurrence of high atmospheric concentrations of the substance. To date, this step has been impossible in view of the great technical difficulties encountered in formulating accurate advance meteorologic predictions of the extremely variable conditions contributing to the occurrence of precise concentrations of individual contaminants. Legal establishment of an alert program based on *smog forecasts* is impossible until this technical program can be resolved.

(2) Present alert standards are based on available information regarding the toxicity of individual contaminants. Most such information, however, is derived from the experience of industrial hygienists who warn that their tables of maximum allowable concentrations for industrial workers cannot be extrapolated for air pollution situations. It must be recognized, therefore, that a great deal more can be learned regarding the toxicity of individual substances present in the atmosphere of urban areas. There remains the addition complication of possible synergistic effects between individual contaminants — effects which are now unknown and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therefore incapable of recognition in an official disaster-prevention program.

(3) Research has failed to show any direct correlation between the intensity of smog in Los Angeles County and the concentrations of any of the contaminants listed by Regulation VII as a basis for the declaraiton of alerts. It may well be that we are not yet monitoring the atmosphere for the specific contaminant or reaction products comprising a true index of smog intensity and of public health disturbances. This remains the *illusive Pimpernel.*

(4) As constituted in Los Angeles, the over-all effectiveness of the disaster-prevention program also may be questioned. After 10 years of intensive effort in establishing air pollution controls over industrial operations, the largest remaining sources of contaminants are motor vehicle exhausts and organic solvents. Refuse burning will be outlawed completely on October 1, 1957, leaving motor vehicle exhausts as the chief contributor of smog-forming organic materials. Unfortunately, this source eludes effective curtailment during alert periods. Law enforcement agencies have been unable to devise a practical plan for halting vehicular traffic[9] should a second or third alert condition be reached. It is conceivable that the closing of industrial establishments during alert periods might even lead to an exaggeration of the over-all pollution problem by motivating thousands of employees to drive their automobiles home at the worst possible time of day.

In spite of problems to be met in formulating air pollution disaster-prevention programs for urban areas, it must be recognized that the possibilities of such disasters — however remote — are an ever-present threat in modern urban communities.

In recognition of this eventuality, the Los Angeles County program has been organized. It represents an in-

tensive effort to establish all possible safeguards against health-disturbing smog episodes, at least until such time as effective and permanent remedial measures may be devised and installed on existing uncontrolled or imperfectly controlled sources of air contamination.

The program requires an annual expenditure of approximately $480,000 for *all* purposes and involves several essential activities: air monitoring, an effective communication system, intensive public information and education efforts, continuing maintenance and development of industrial shut-down plans, and constant research efforts to improve the system and the standards of contaminant concentrations.

Even as great advances have been made in the control of air pollution in Los Angeles County during the past 10 years, it is to be hoped that continued technical advances will point toward areas where the disaster-prevention program may be further improved so that the health of five and one-half million persons can be protected to the fullest possible extent.

REFERENCES

1 All changes in the Regulation, of course, must result from legal enactments by the Air Pollution Control Board.

2 *Clean Air for California*, Calif. State *Dept.* of Public Health, March, 1955.

3 See also, J. Cyril Romanovsky, James R. Taylor, et al. *Air Monitoring of the Los Angeles Atmosphere With Automatic Instruments.* Presented at the Annual Meeting of the Air Pollution Control Association, Buffalo, New York, May 21, 1956.

4 In this instrument, infrared rays from two separate nichrome sources are passed alternately, at a frequency determined by a chopper, through 2 parallel cells, converging on a single detection cell containing a known concentration of carbon monoxide in argon. One of the parallel cells contains pure nitrogen as a reference gas, while through the other flows the air to be sampled.

The radiation received by the detector cell from each beam, after it has passed through its respective sample or reference cell, causes the carbon monoxide to be heated and to expand against the condenser plate of a microphone housed in the detection cell. If one beam contains more infrared radiation than the other, the heating and expansion of the carbon monoxide in the detector cell will be greater with one than the other, the pattern of occurrence of this phenomenon being also dependent upon the chopper frequency.

In actual practice, the instrument operates on a null balance principle, which

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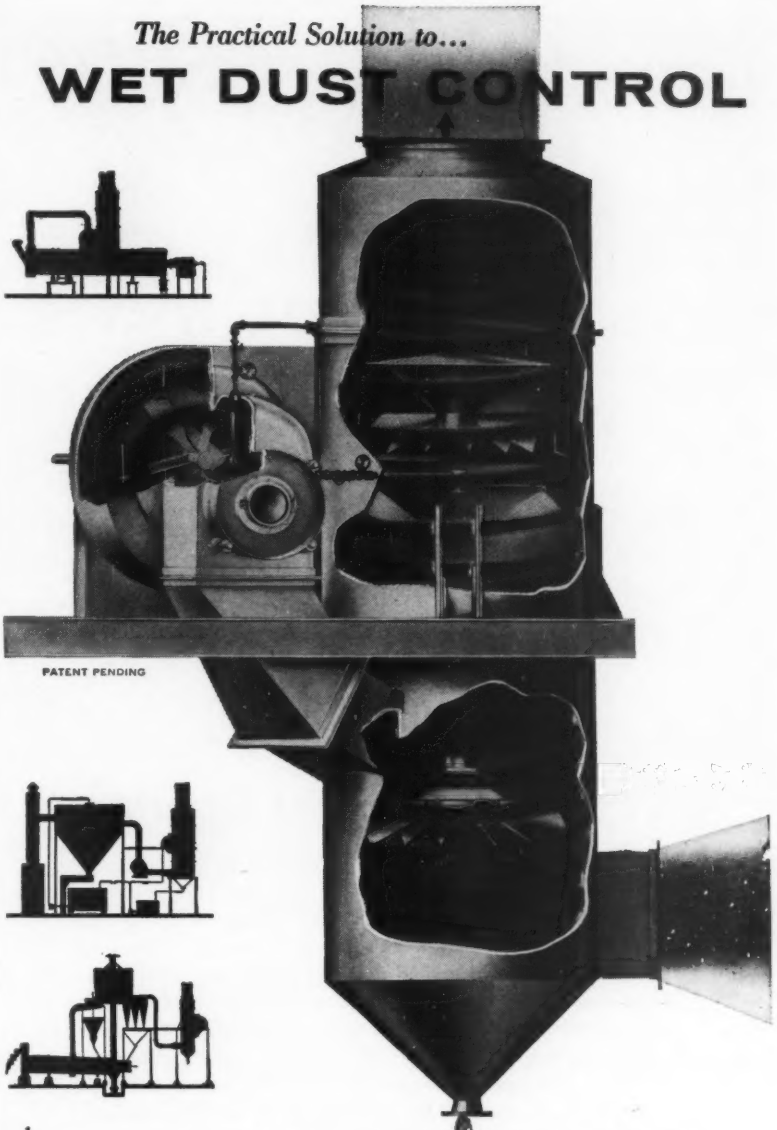

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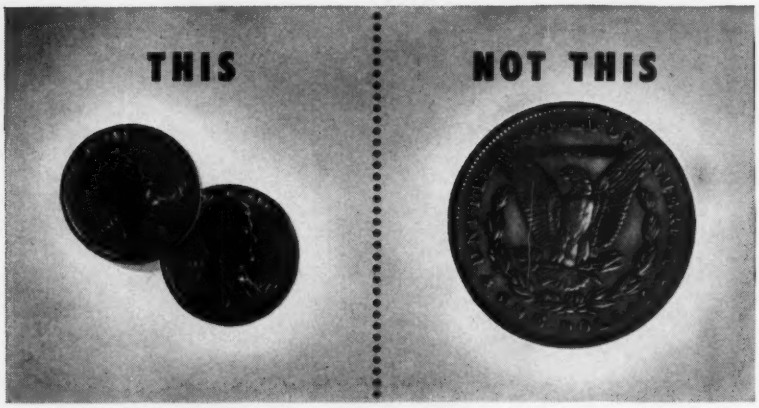

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means that the condenser plate is never actually permitted to vibrate. This is accomplished by means of a feedback mechanism through which it is possible to control the radiation output of the reference source relative to the quantity being received by the cell through the sample path. By this means, the detector cell actually receives the same amount of radiation from both sources regardless of the portion of radiation being transmitted through the sample cell which is absorbed there during transmission. Since the difference between the 2 beams is compensated by the feedback mechanism, the amount of compensation necessary will be proportional to the amount of carbon monoxide present in the sampled gas which absorbed the radiation in the sample cell. This can be translated and recorded in terms of concentration of carbon monoxide in ppm. by volume.

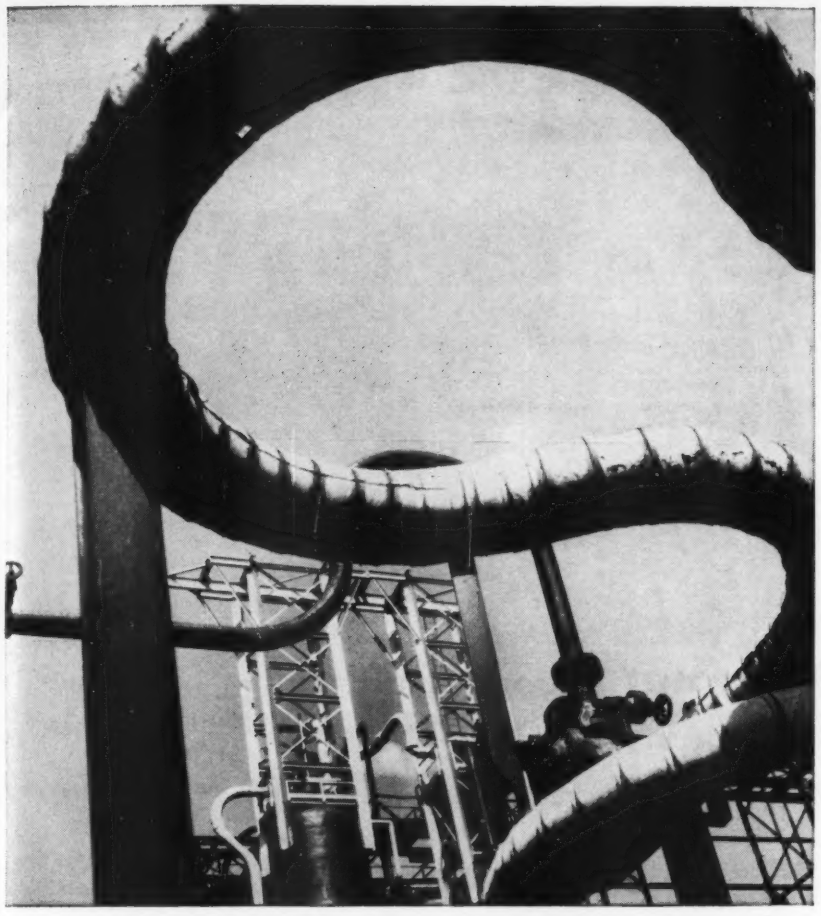
[6] The instrument utilized is actually designed to measure both nitric oxide and nitrogen dioxide simultaneously and accomplishes this in the following manner: For nitrogen dioxide (NO_2), air is drawn through an absorption column at the rate of 225 ml./min., countercurrent to a flow of Saltzman absorbing solution at the rate of 2.16 ml./min. Color produced by the reaction between nitrogen dioxide and Saltzman reagent is measured photometrically and is continuously recorded, as ppm. (by vol.) of nitrogen dioxide.
Sampling for nitric oxide (NO) through a separate sampling stream, is identical with that for nitrogen dioxide except that the air flow rate is 235 ml./min. and that, just prior to passing through the absorption column, a measured concentration of ozone is added to the sample stream in order to convert the nitric oxide to nitrogen dioxide. The color produced by the total nitrogen dioxide present in this sample stream is also recorded on the strip chart as ppm. nitrogen dioxide, the difference between the 2 concentrations being attributable to the oxidized nitric oxide.

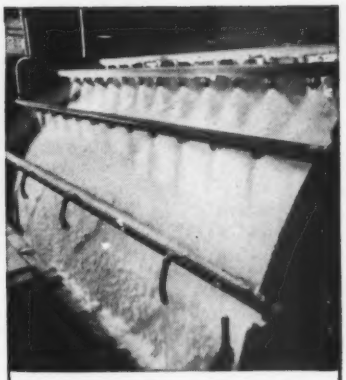
[6] In this instrument air is drawn through an absorption column at a rate of 0.33 cfm., countercurrent to the flow of hydrogen peroxide absorbing solution at a rate of 3.3 ml./min. The sulfur dioxide present in the sample stream is simultaneously absorbed and oxidized to form sulfuric acid, the concentration of which is determined by measuring the change in electrical conductivity of the absorbing solution before and after contact with the sample stream. This change is recorded as ppm. (by vol.) of sulfur dioxide.

[7] Rule 156 names the contaminants serving as triggers for the declaration of alerts. These include ozone, sulfur dioxide, carbon monoxide and oxides of nitrogen.

[8] Under Rules and Regulations of the APCD, permits must be secured from the District prior to the construction and operation of any device capable of emitting, or designed to control the emission, of air contaminants.

[9] There are presently 2,700,000 motor vehicles registered in Los Angeles County, and 53 local enforcement agencies having jurisdiction over traffic control in various areas of the County.





Kraft paper pulping operations have their own odor characteristics. Even their "sour cabbage" smell has been effectively controlled with Airkem.

Airkem installations are simple to operate and low in cost. No change is required in process or plant construction.

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Is your process odorous? Airkem maintains the most extensive odor research laboratory in the world, as well as an international organization of trained field representatives to help solve your problems. If your company has a problem with odors from petroleum wastes, kraft pulping, fertilizer processing, paint baking, or any other industrial process, why not ask Airkem for help?

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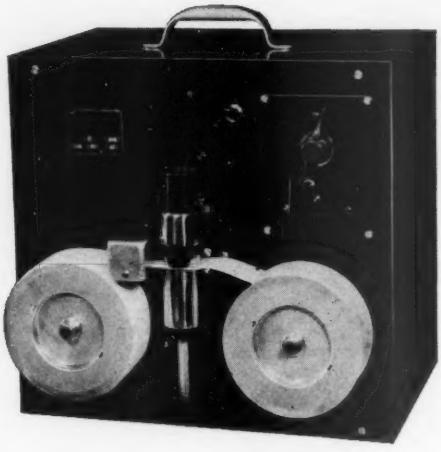

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Like an increasing number of large cities throughout the country, Cincinnati is conscious of the undesirability of polluted atmosphere. Similarly, an increasing number are depending on the A.I.S.I. Sampler to record for them what contamination is in the atmosphere. They have found, too, that because of its low cost, the A.I.S.I. Sampler can be used in quantity to give complete coverage of the city. And, of course, it operates quietly and continuously 24 hours a day.

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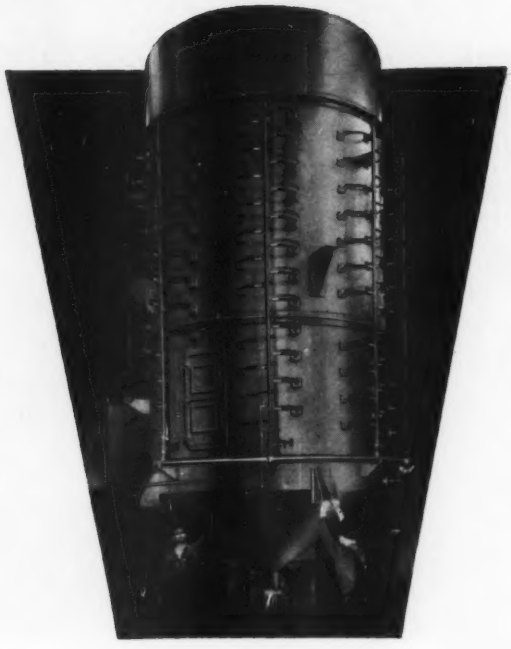

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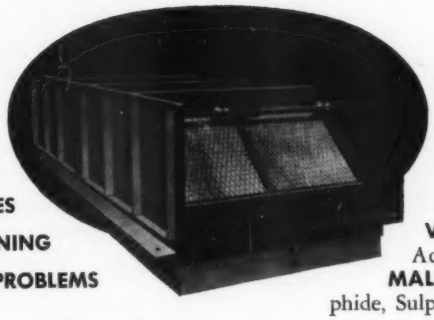

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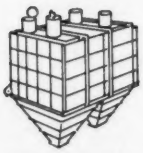

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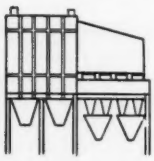

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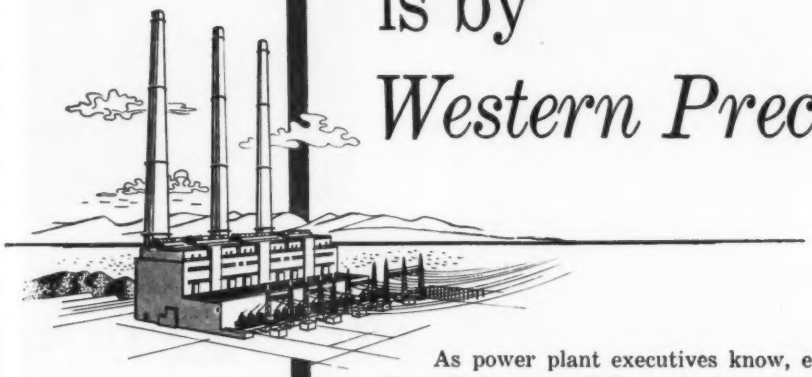

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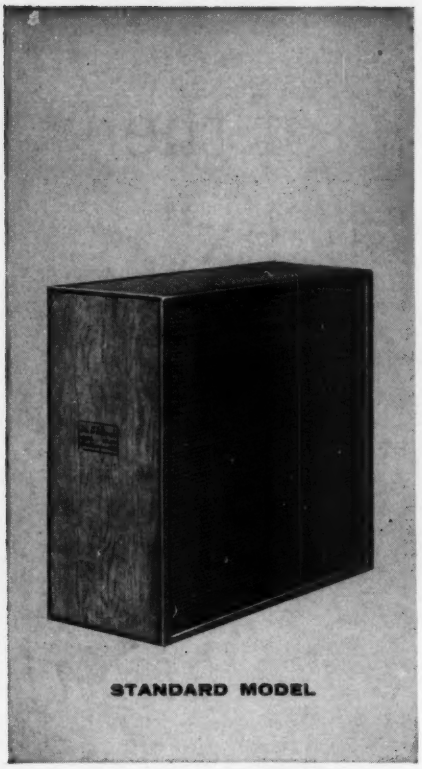

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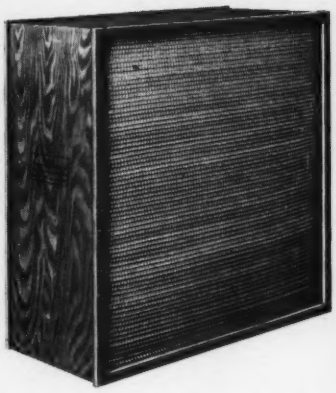

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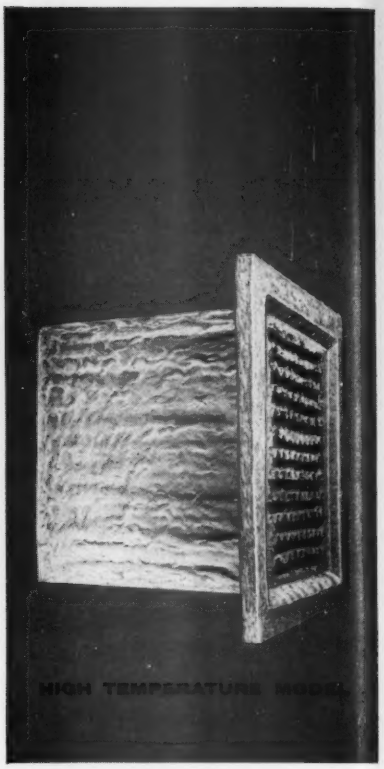

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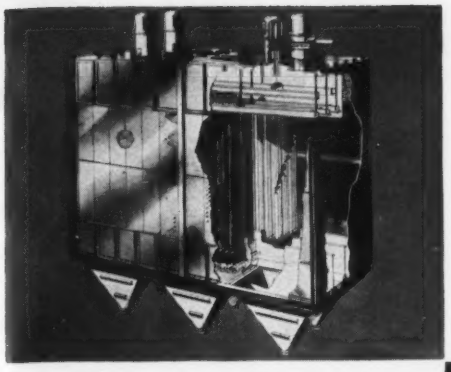

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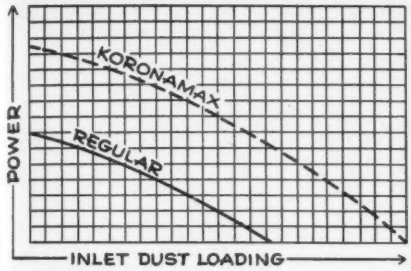
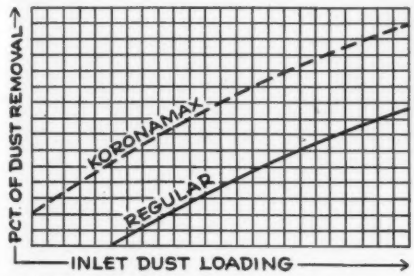
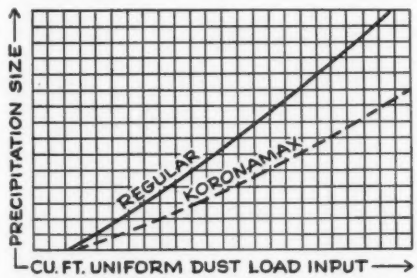


INCREASED POWER—The evenly spaced discharge points of "Koronamax" Electrodes reduce the arc-over tendency and permit increasing power input.



HIGHER EFFICIENCY—Replacement of regular electrodes with "Koronamax" Electrodes allows higher power input — greatly increased efficiency.



SMALLER SIZE—In new installations desired efficiency may be obtained with smaller unit when "Koronamax" Electrodes are used.

CONVENTIONAL ELECTRODES

"KORONAMAX" ELECTRODES

"KORONAMAX" ELECTRODES increase efficiency and capacity of electrostatic precipitators

"Koronamax" Electrodes developed by Koppers are now in service in several different applications and their *controlled* corona discharge has resulted in greatly increased capacity and efficiency. This unique type of precipitator electrode may solve *your* gas cleaning problem.

Koppers' experience, constant research and extensive field testing have led to this important advance in precipitator design. Check with Koppers to see if "Koronamax" Electrodes can help you get top precipitator efficiency. For more information, write: KOPPERS COMPANY, INC., 9405 Scott Street, Baltimore 3, Md.

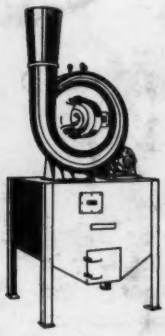
KOPPERS

ELECTROSTATIC PRECIPITATORS

Engineered Products Sold with *Service*

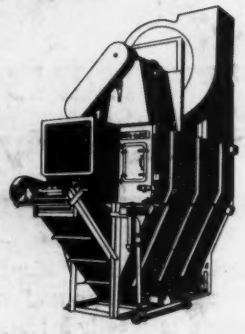
QUESTION: *Why AAF dust control?*

ANSWER: *The industry's most complete line of equipment.. Backed by the world's most experienced dust control men!*



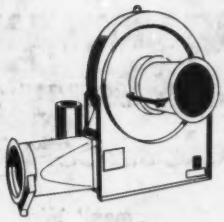
Type D ROTO-CLONE

For moderate loadings of dry, granular particles



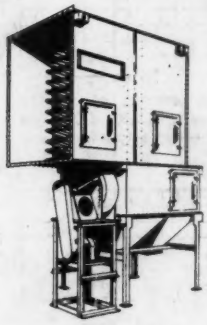
Type N ROTO-CLONE

For heavy-duty loadings of all sizes



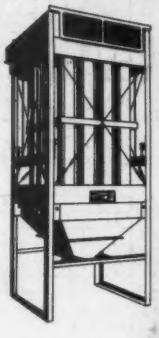
Type W ROTO-CLONE

For medium concentrations of fine particles



AMERclone

For high concentrations of dry, granular particles in large volumes



AMERjet

For extremely fine particles and materials that should be reclaimed dry

AAF herman nelson

American Air Filter
COMPANY, INC.

256 Central Avenue, Louisville 8, Kentucky

American Air Filter of Canada, Ltd., Montreal, P. Q.